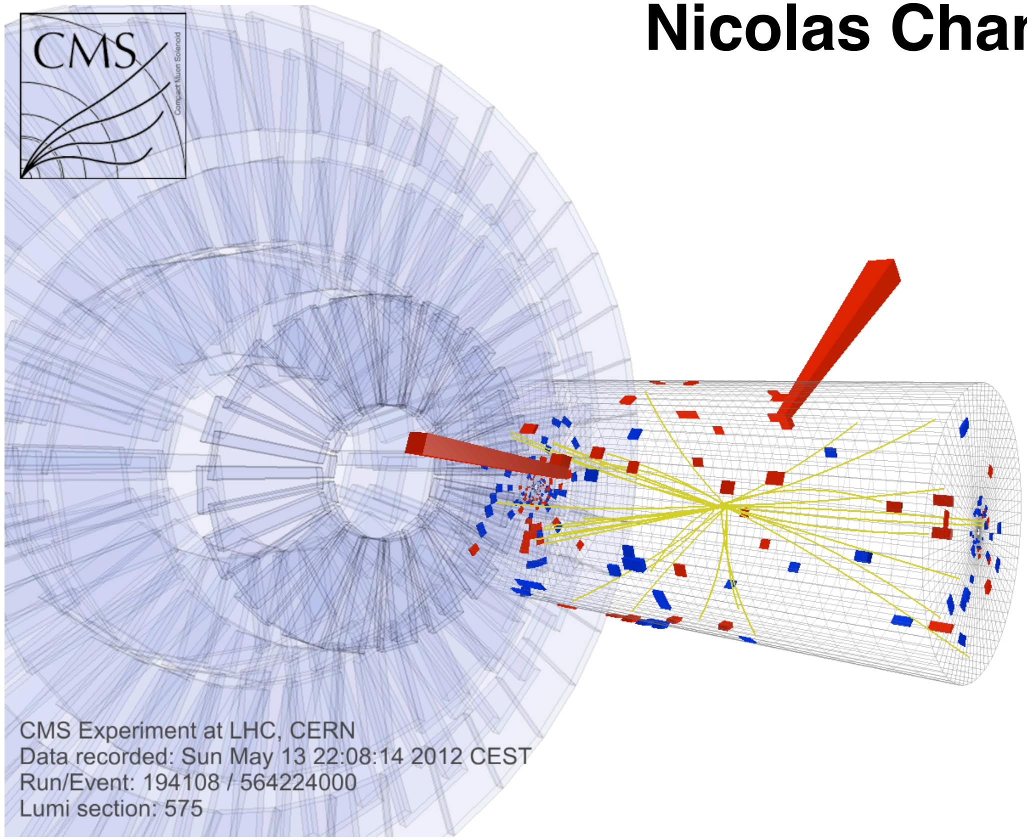
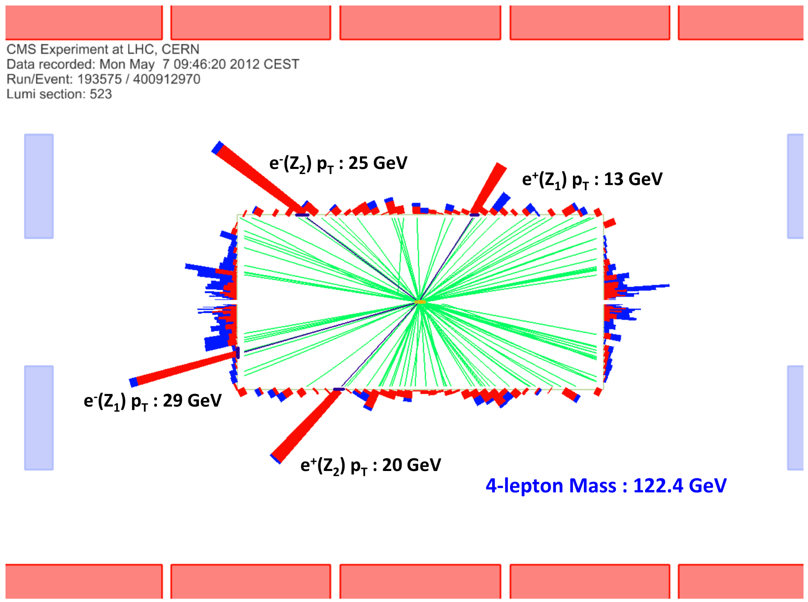
ETH Institute for Particle Physics

Higgs boson searches at CMS

20/01/2014 - CPPM, Marseille

Nicolas Chanon - ETH Zürich





Outline

The Higgs boson

Presentation of LHC and CMS

Main Higgs analyses

New particle properties

Conclusions

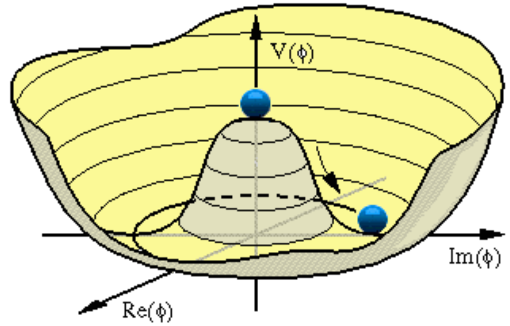
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow WW \rightarrow 2l2\nu$
- $H \rightarrow bb$
- $H \rightarrow \tau\tau$

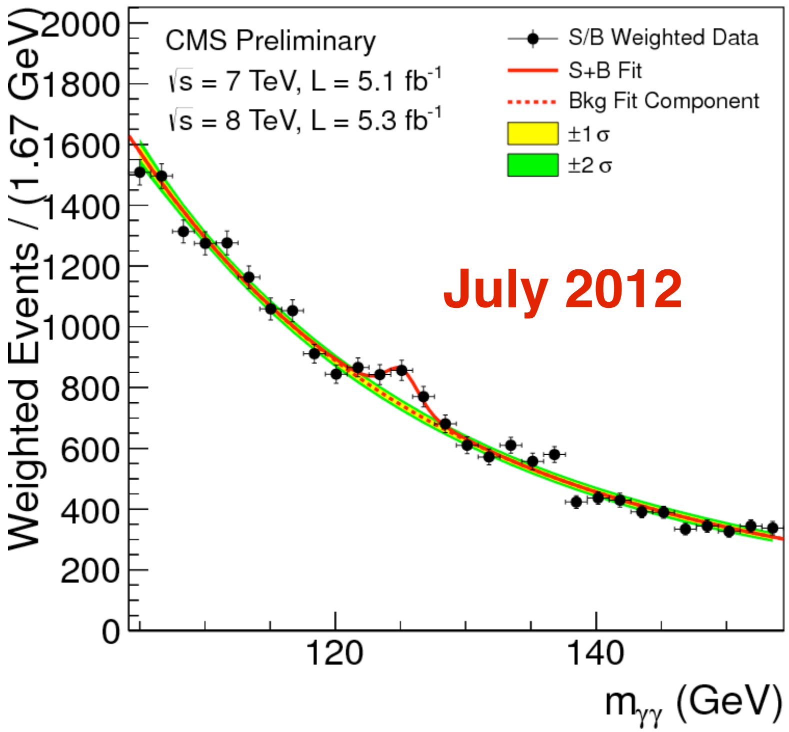
Run I legacy analyses

- Mass
- Couplings
- Spin

Higgs boson in the standard model

Higgs boson is predicted in the standard model of electro-weak interaction since 1967 [Glashow, Weinberg, Salam].
Higgs mechanism:
- **Scalar field** breaking spontaneously the electro-weak symmetry
- **Longitudinal degrees of freedom** absorbed in $W^{\pm}$ and Z^0 gauge bosons
- Higgs boson gives masses to leptons and quarks through **Yukawa couplings**



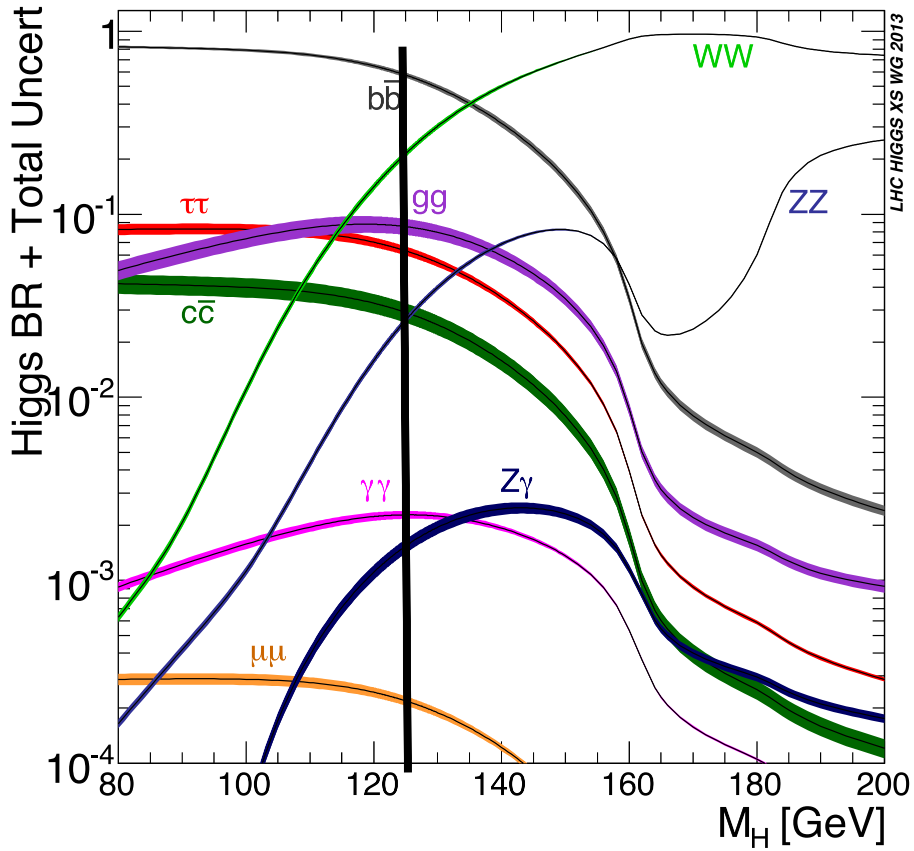


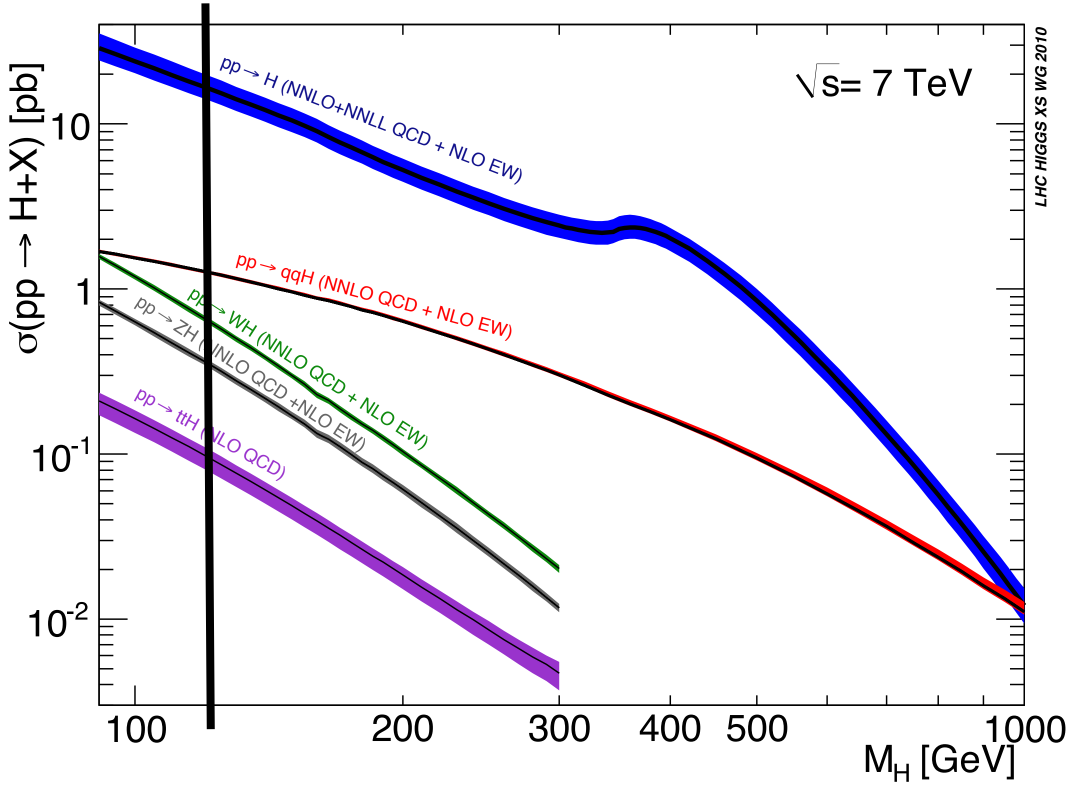
New boson discovered by ATLAS and CMS collaborations in July 2012 in the Higgs boson searches, with a **mass around 125 GeV**

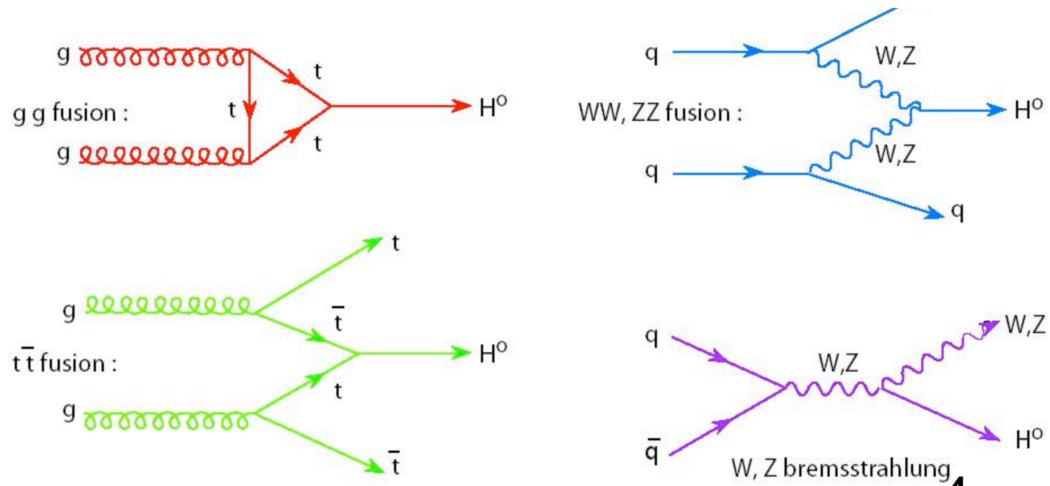
Is it the standard model Higgs boson?

Higgs boson channels at LHC

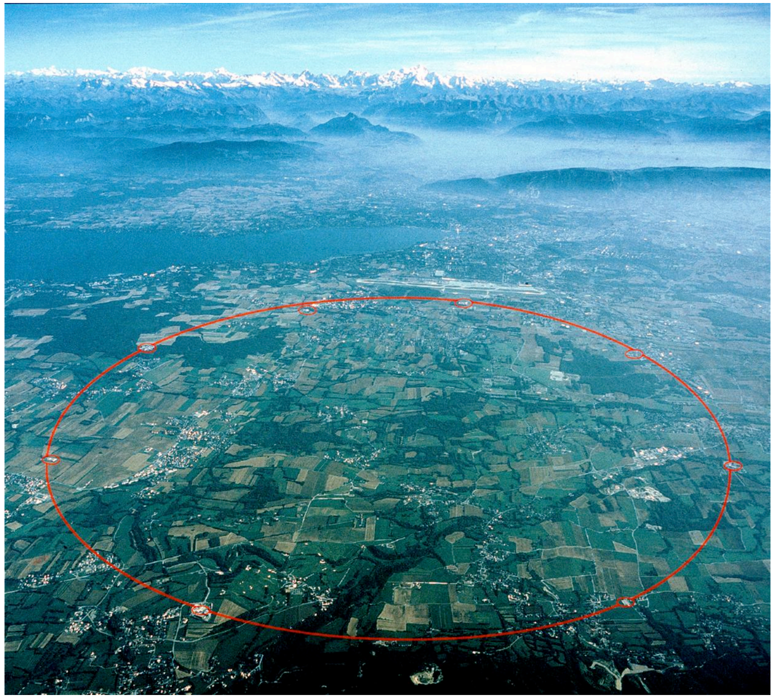
- At the LHC, the main **Higgs production** mechanism in the SM is **gluon fusion** followed by **VBF** and associated production with W,Z or tt
- **Essential to probe both boson and fermion decay**



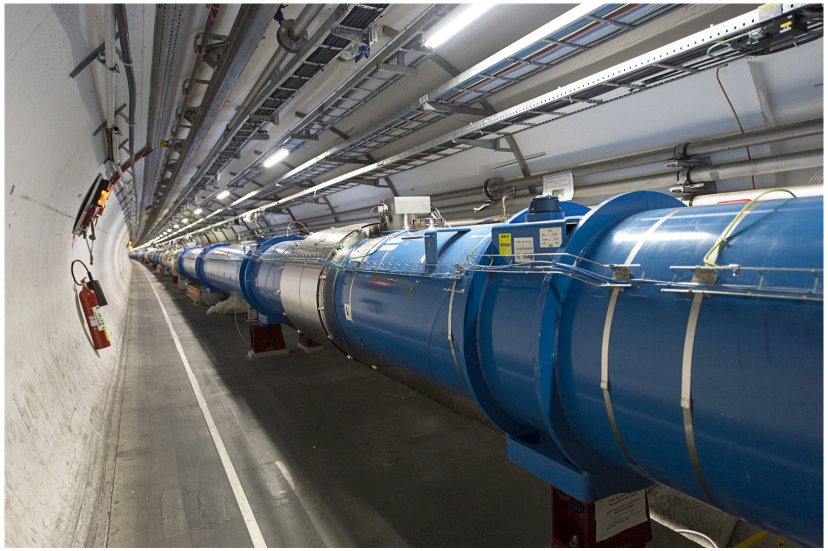


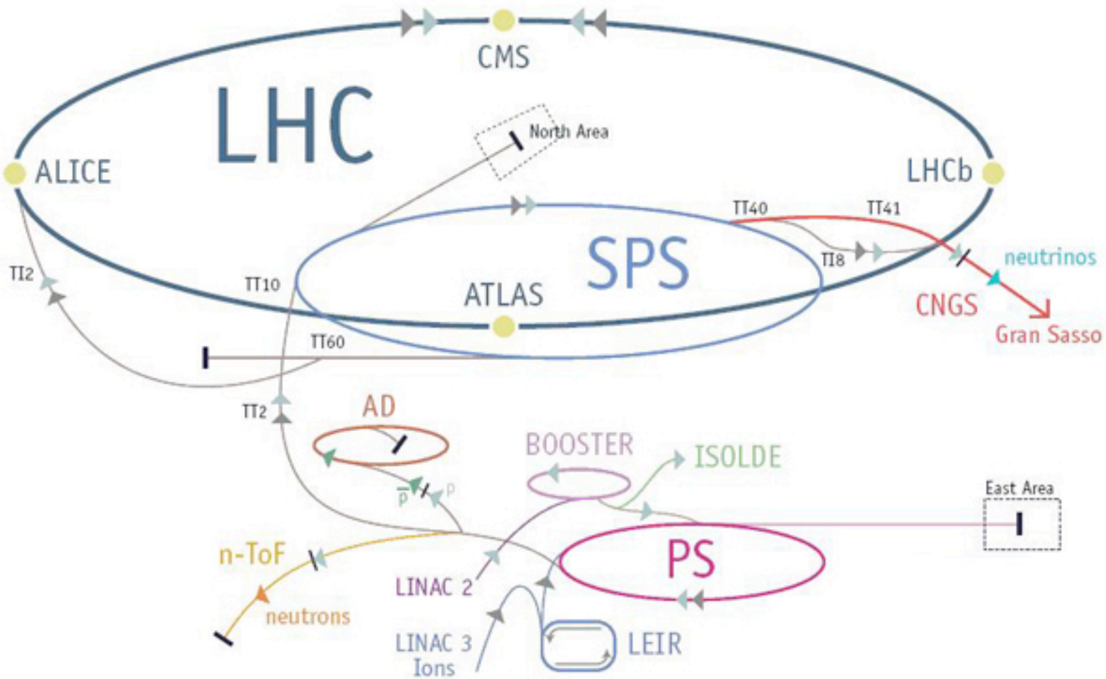


Large Hadron Collider (LHC)

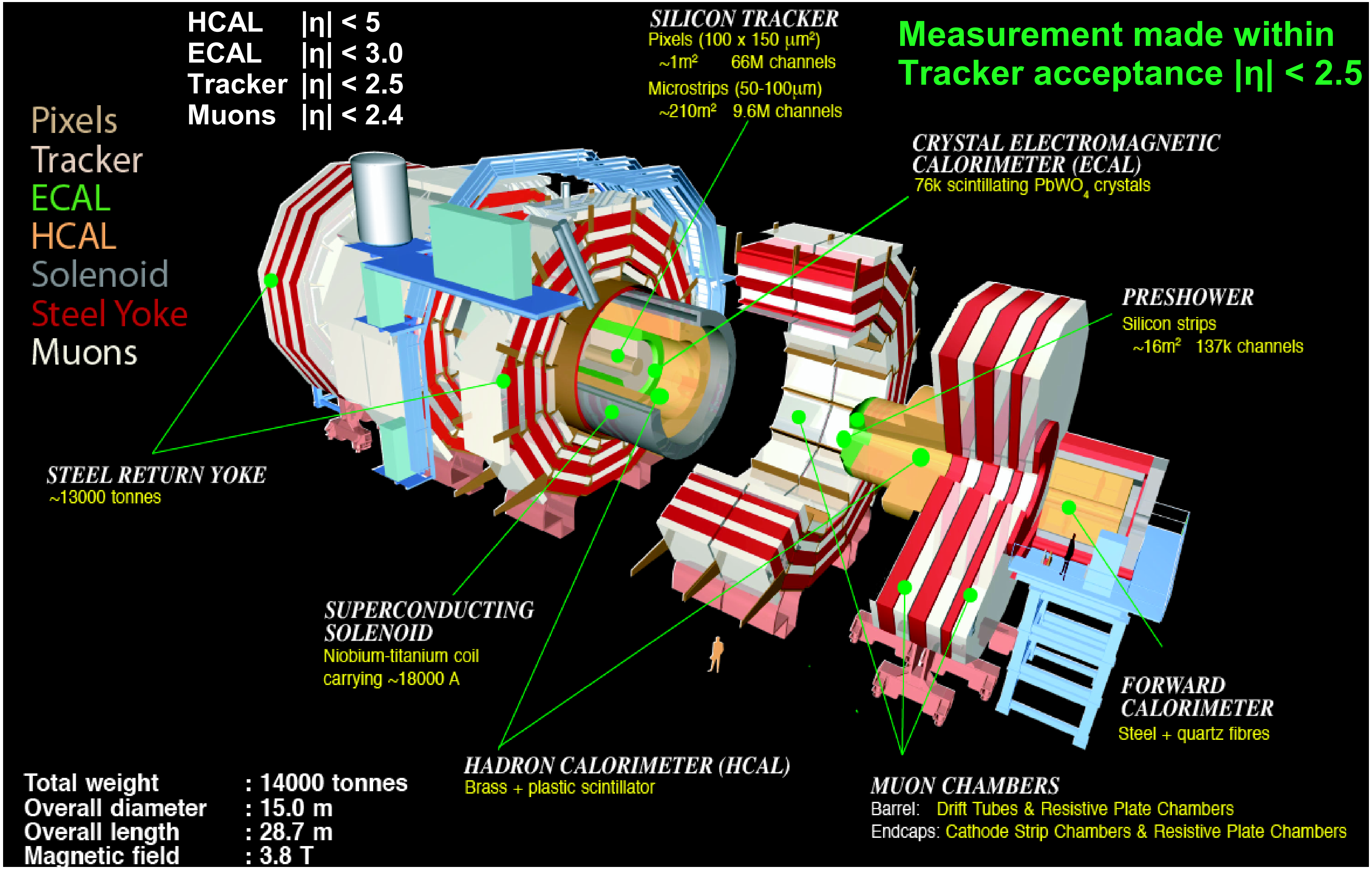


- **Proton-proton** collider at **CERN**, Geneva
- 27 km circumference, fully supra-conducting magnets at 100m depth
- 7 TeV center of mass energy in 2010 and 2011, 8 TeV in 2012
- Instantaneous luminosity: reached peak 7.7×10^{33} $cm^{-2}s^{-1}$



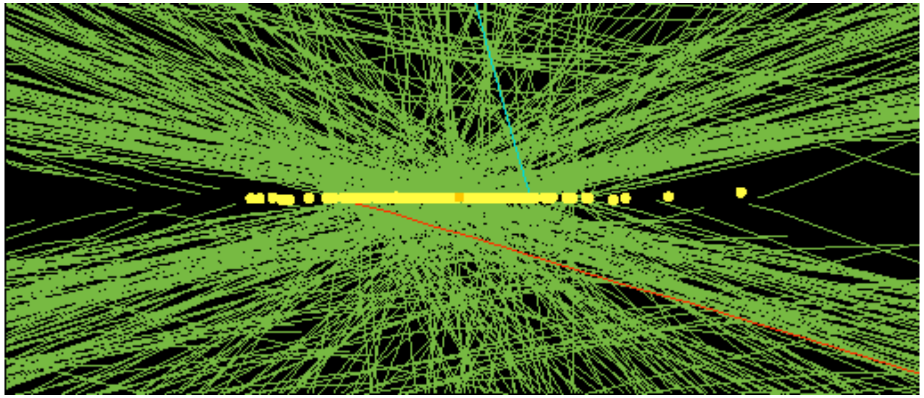


Compact Muon Solenoid (CMS) detector



Luminosity conditions

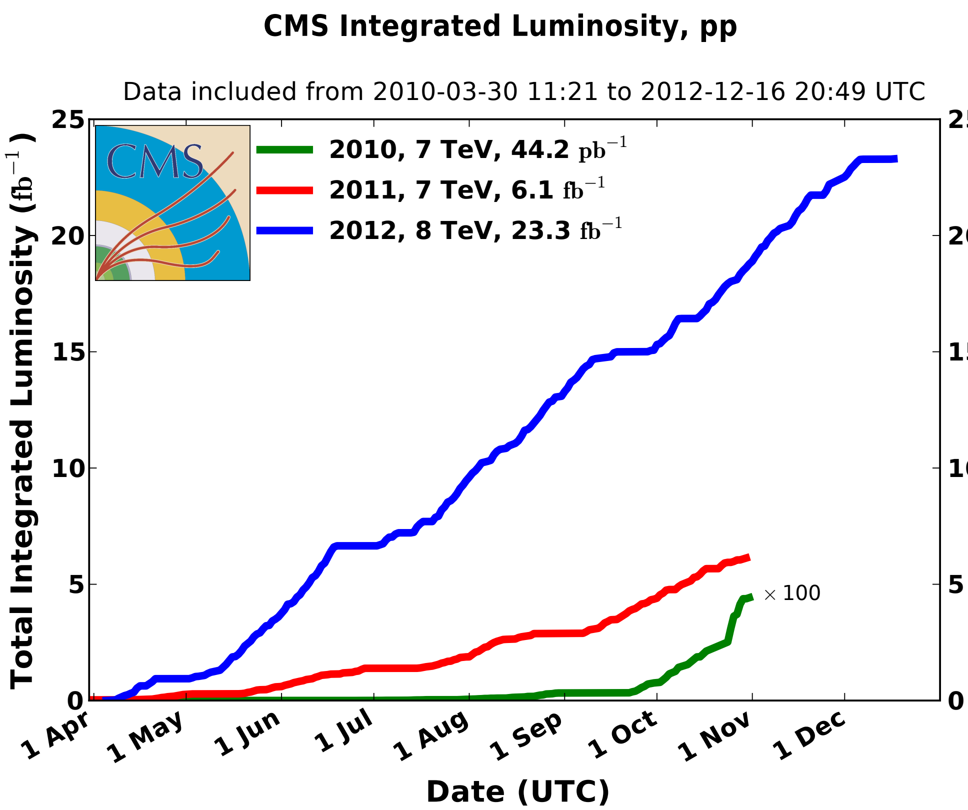
Event with 70 reconstructed vertices (special run)

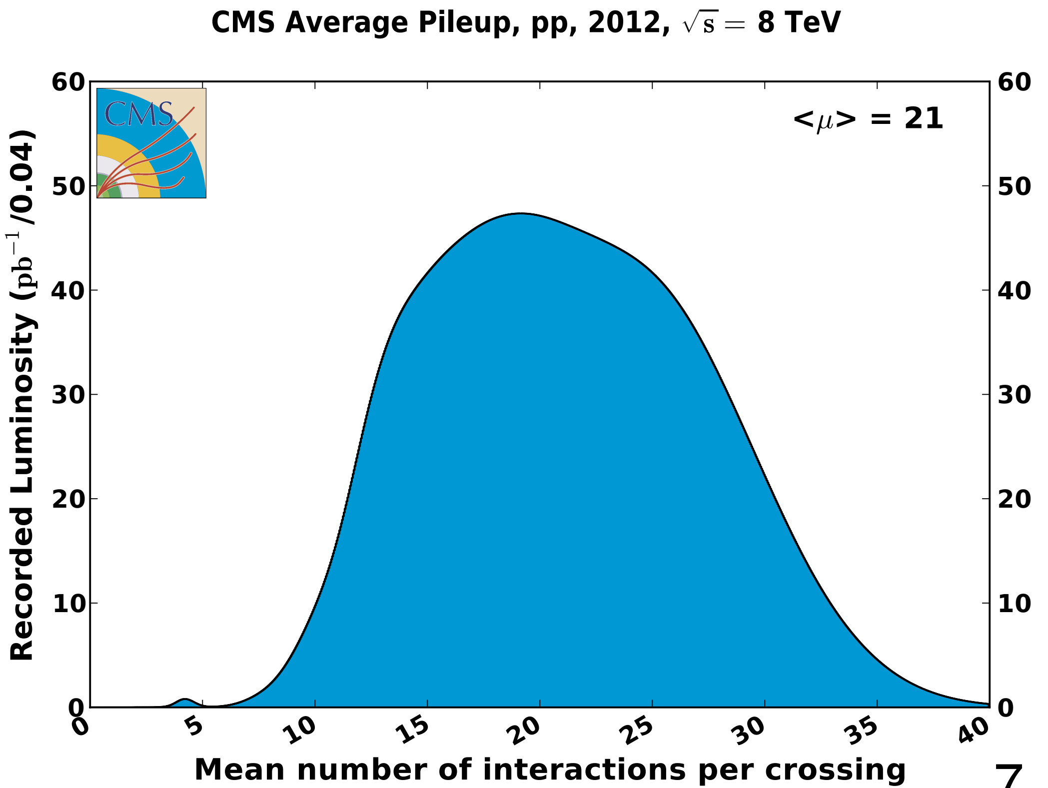


Analyses presented in this talk are using:

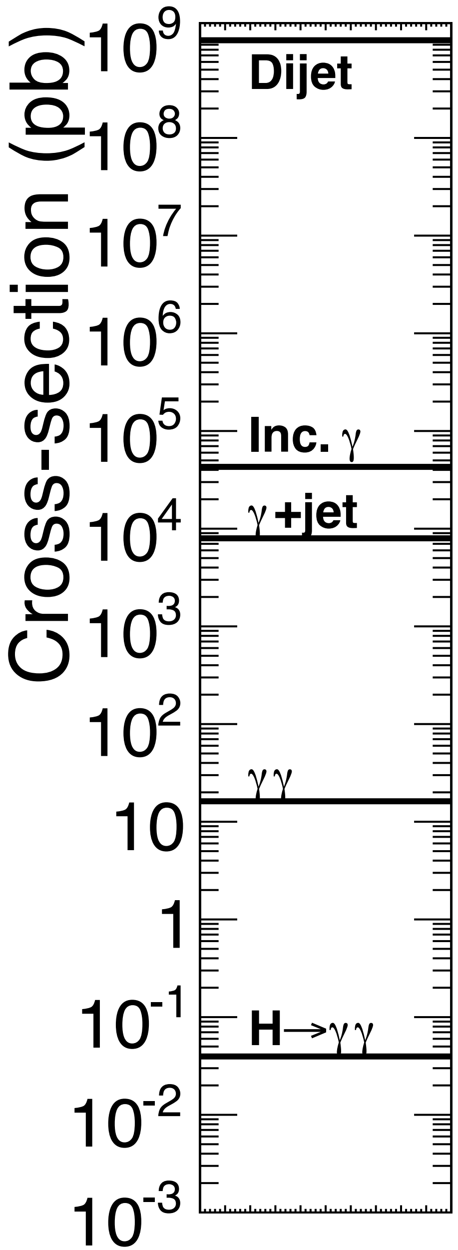
- **5.1 fb-1 of 7 TeV data** in 2011
- **Up to 19.6 fb-1 of 8 TeV data** in 2012

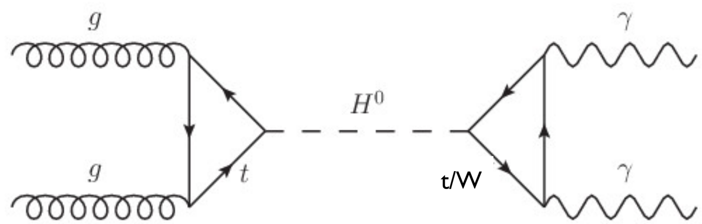
Pileup mean interaction ~21 in 2012 (~10 in 2011)

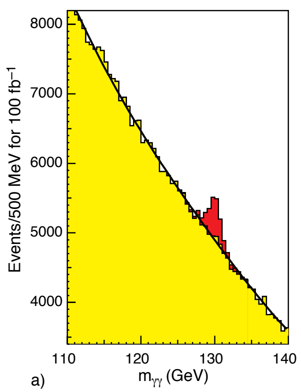




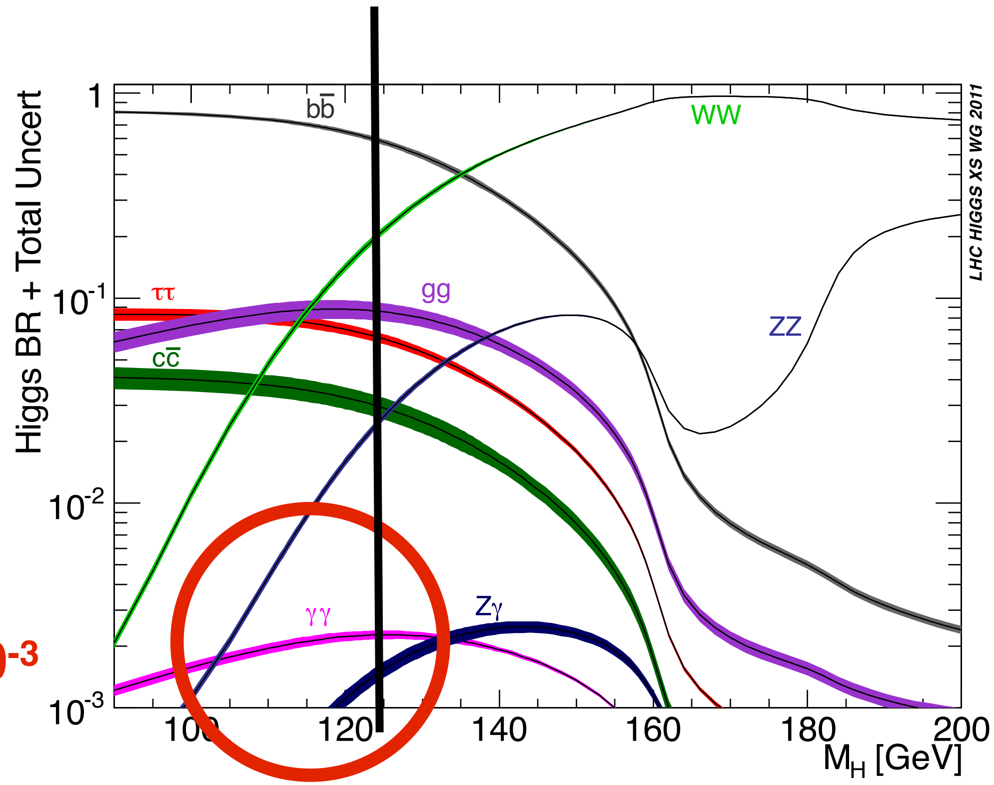
H→γγ



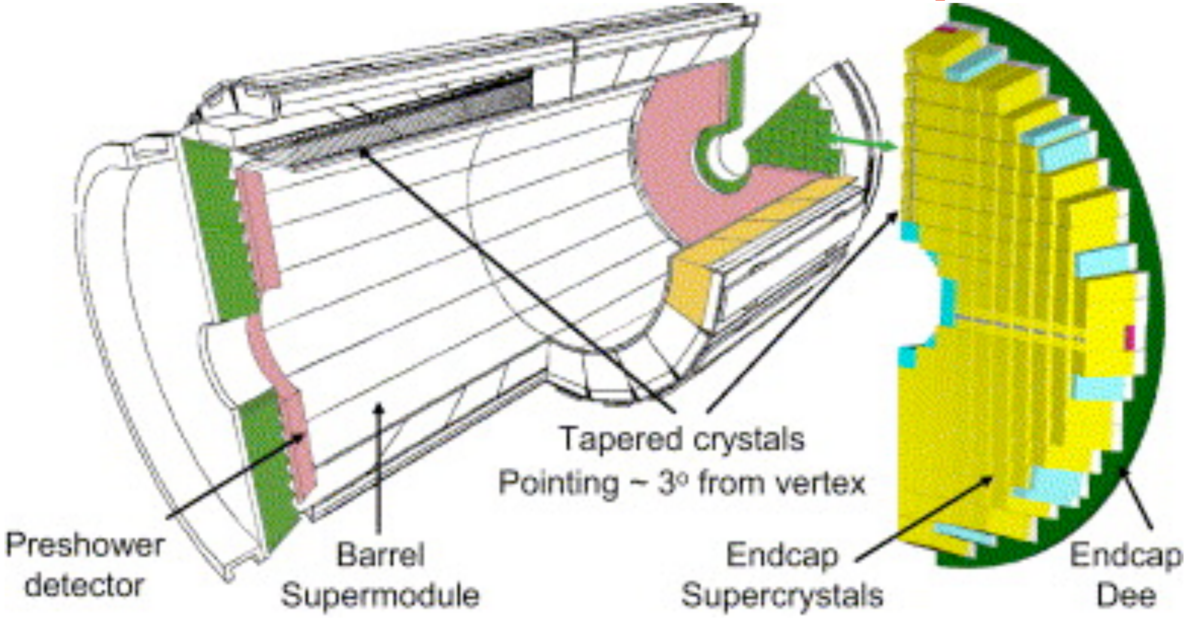




BR(H→γγ)~2.10^{-3}



CMS electromagnetic calorimeter (ECAL)



CMS Electromagnetic calorimeter (ECAL) :

- 75848 $PbWO_4$ crystals
- **Excellent** energy resolution (design: 1% for H→γγ barrel photons)

The **ECAL** is made of scintillating crystals of PbWO4 :

-**Barrel** : 36 “supermodules” with 1700 crystals each (coverage $|\eta|<1.48$)

-**Endcaps** : 268 “supercrystals” with 25 crystals each (coverage $1.48<|\eta|<3.0$)

A **preshower** made of silicon strip sensors is located in front of the endcaps ($1.65<|\eta|<2.6$)

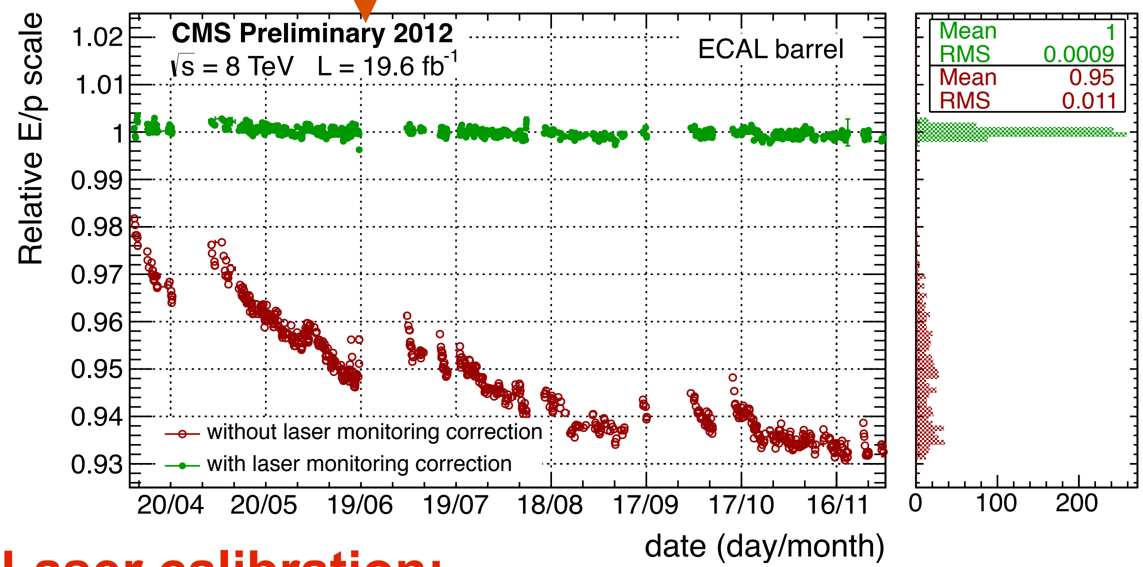
Energy resolution (measured in electron test beam) :

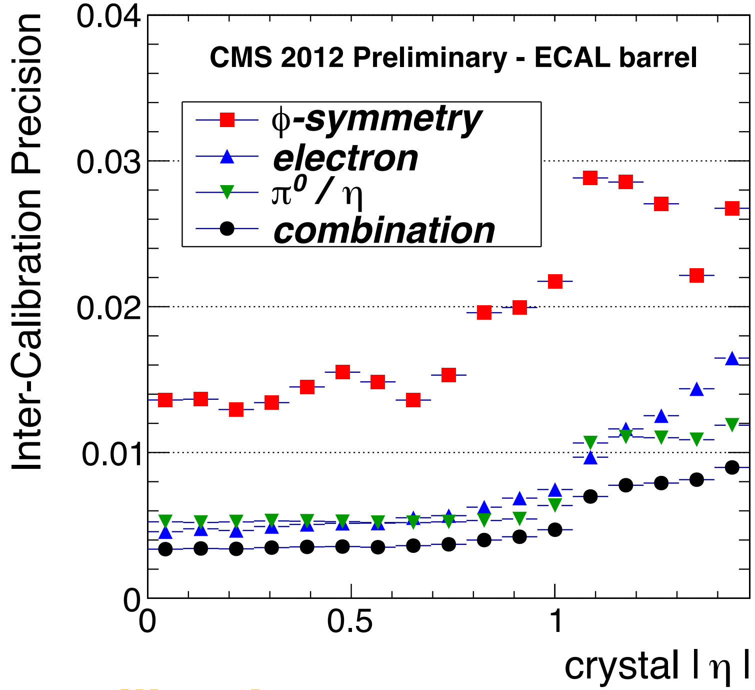
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus \frac{b}{E(GeV)} \oplus c$$

a = 2.8% stochastic term
b = 12% noise term
c = 0.3% constant tern

ECAL Calibration

Laser monitoring → **Crystal Intercalibration ($\pi^0 \rightarrow \gamma\gamma$)** → **Cluster energy correction (MC)** → **Energy scale ($Z \rightarrow ee$)**





Laser calibration:

- Correct for ECAL crystals **transparency loss due to electromagnetic damage**
- RMS stability after corrections 0.09% (barrel), 0.28% (Endcap)

Inter-calibrations

- Correct for response non-uniformity
- Use π^0 and η (mass), **φ-symmetry** (minimum bias), **W→eν** (E/p)
- **Precision**: better than **0.5% in central barrel**

H→γγ analysis

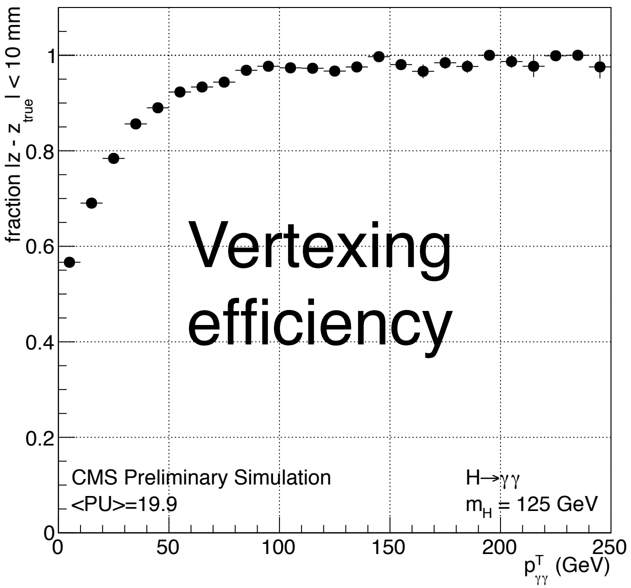
HIG-13-001

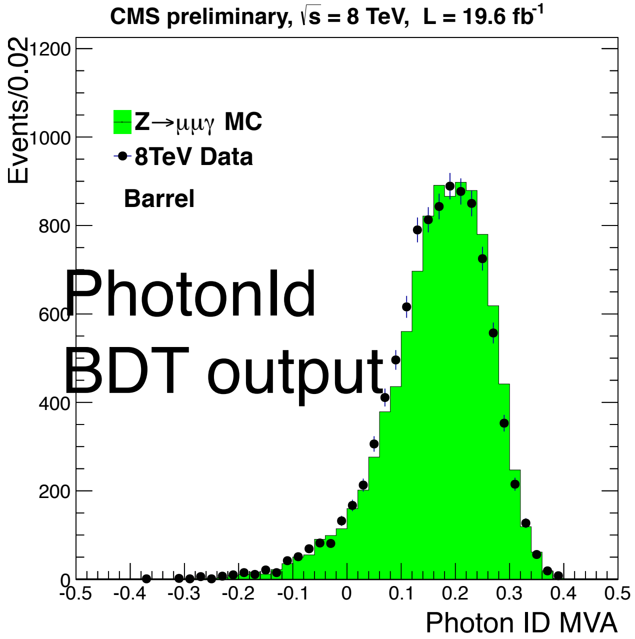
- **Look for small signal peak (small BR) over large background**
- **Main analysis is MVA - cut-based analysis and 2nd MVA analyses as cross-checks**
- Select **two high pt isolated photons** from the same **vertex**

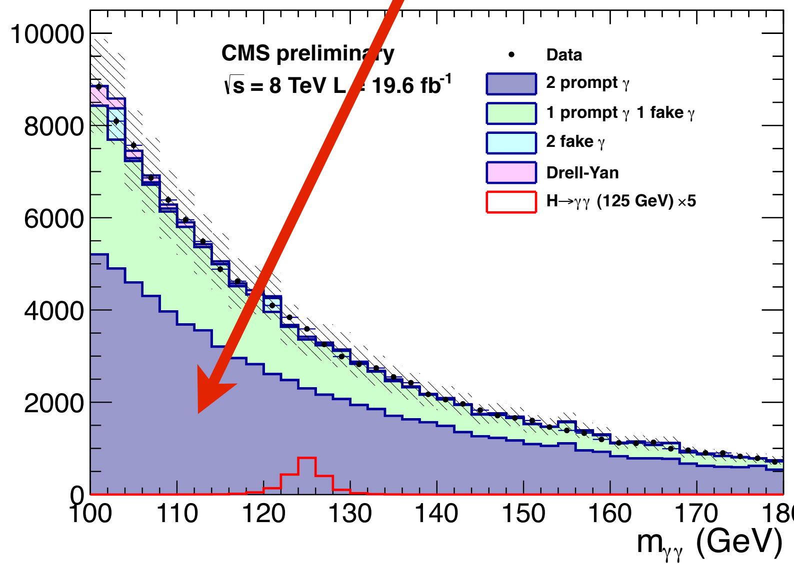
- **Vertexing BDT**: tracks, diphoton kinematics, conversions

- **Photon identification BDT** to reject jets faking photons: shower shape and isolation

Large background from diphoton continuum (~70%) (after photon Id)





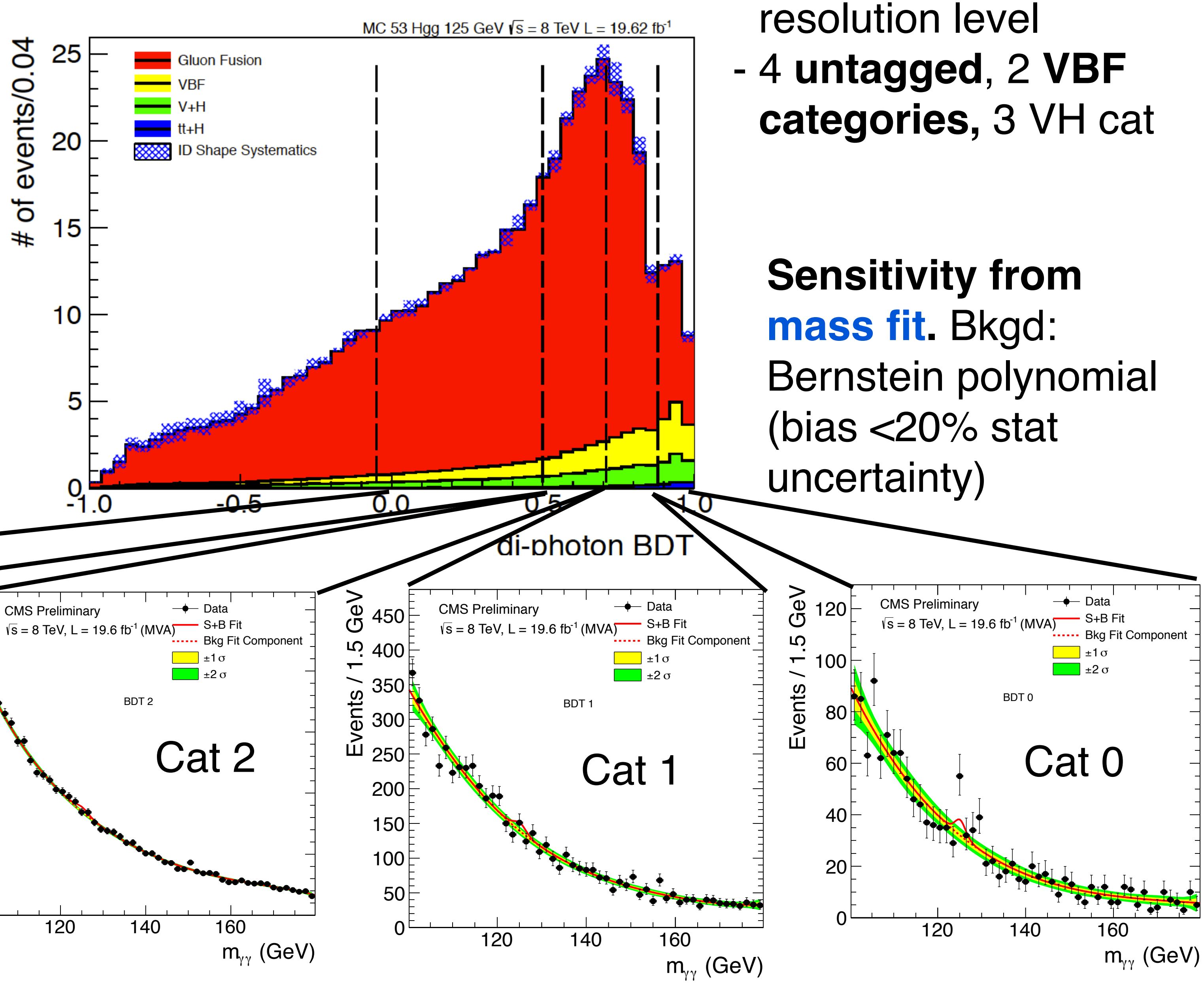


H→γγ: categories

HIG-13-001

Categories:
- Defined with s/b and resolution level
- 4 **untagged**, 2 **VBF categories,** 3 VH cat

Diphoton BDT
- Mass independant
- Kinematics, vertexing, PhotonId output, energy resolution variables



Sensitivity from mass fit. Bkgd: Bernstein polynomial (bias <20% stat uncertainty)

H→γγ mass resolution

HIG-13-001

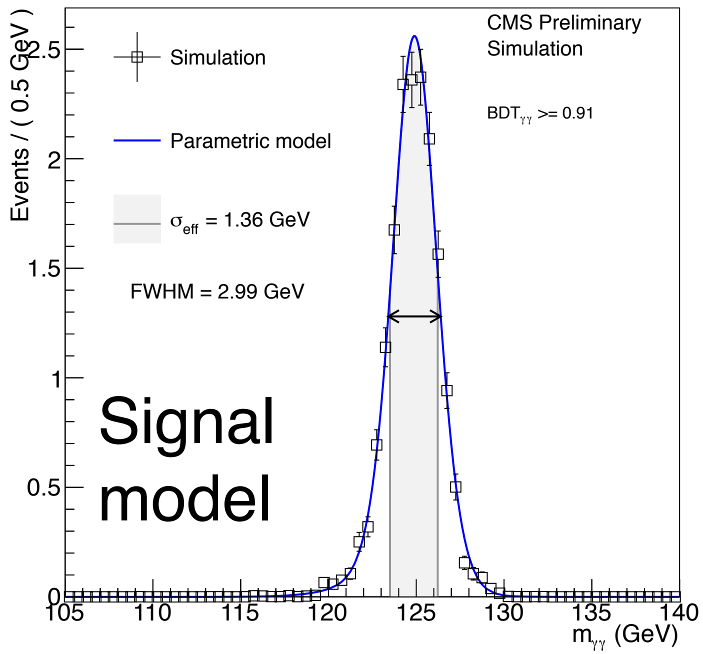
Laser monitoring → **Crystal Intercalibration ($\pi^0 \to \gamma\gamma$)** → **Cluster energy correction (MC)** → **Energy scale ($Z \to ee$)**

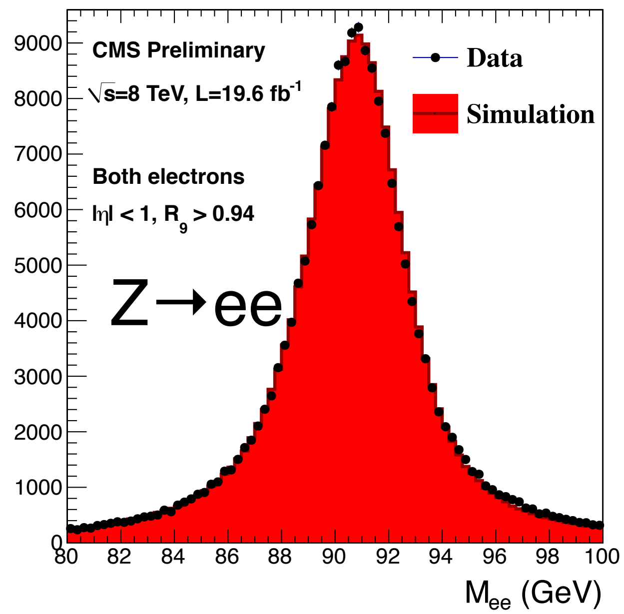
Cluster energy corrections

- Correct for **energy loss** in the **material** upstream ECAL and in ECAL cracks
- Use **geometry**, **shower profile**, energy in **preshower**
- **Energy regression: 1-2% mass resolution**
- **Best untagged category**: 1.36 GeV effective sigma (narrow shower shape in barrel or high diphoton p_T events)

Energy scale:

- Correct for data/MC residual differences in scale and resolution using Z mass shape
- Stable along data-taking period





H→γγ MVA results

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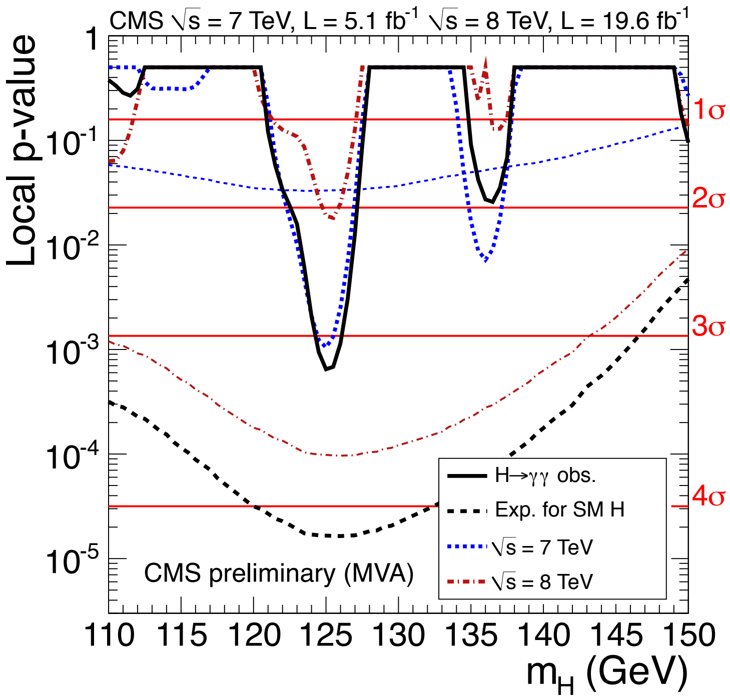
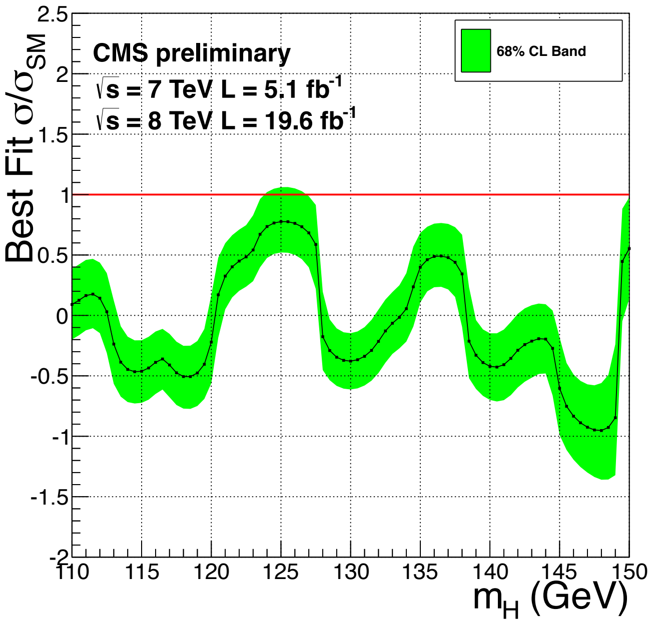
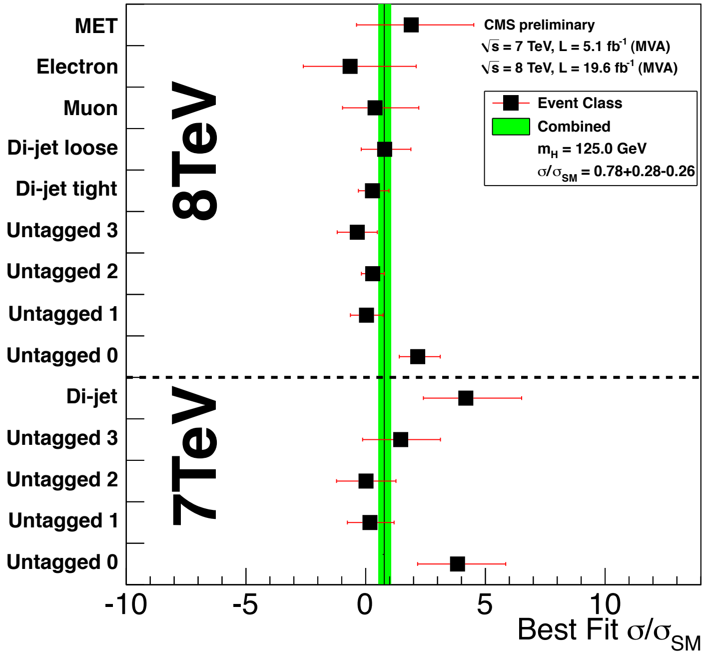
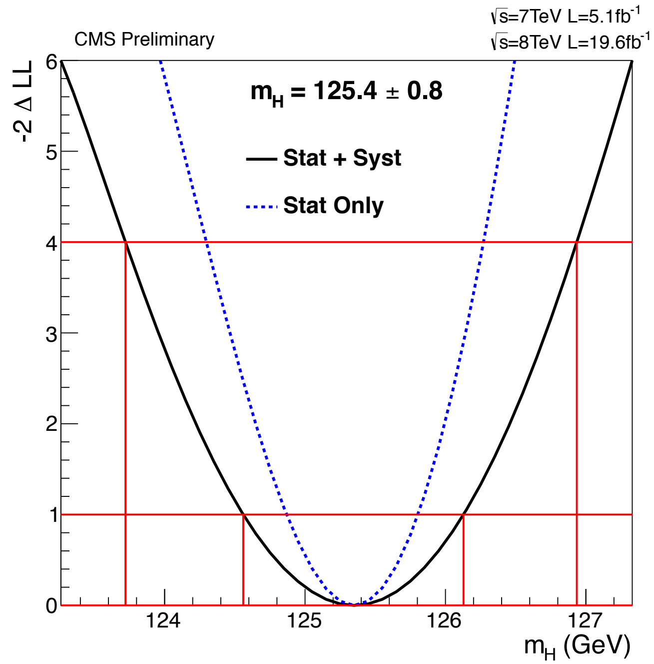






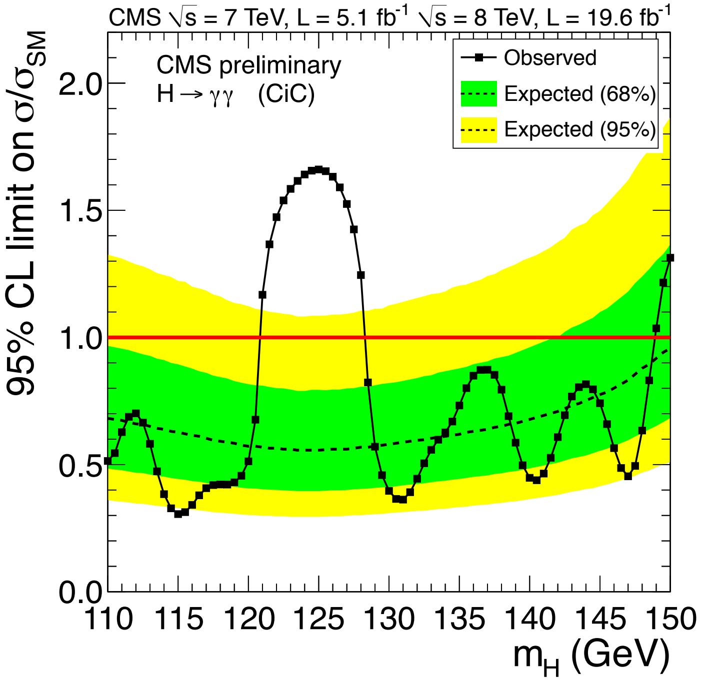
MVA

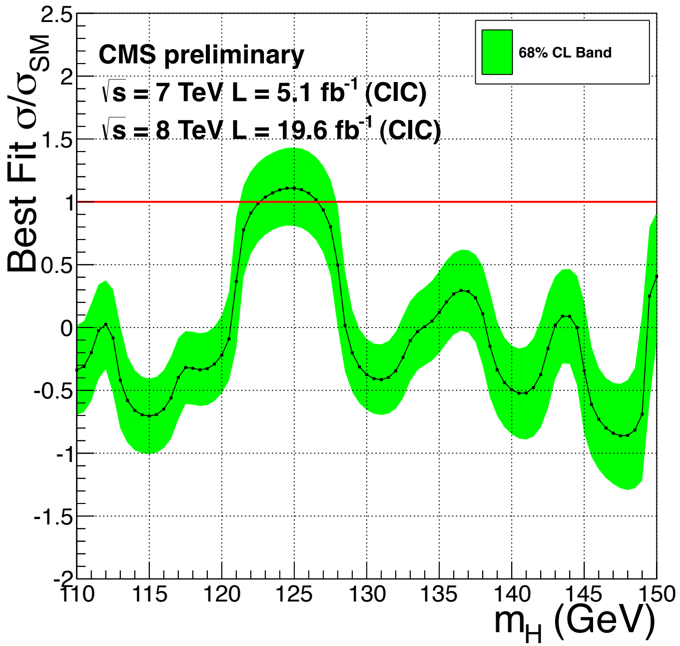
- **Observed local significance above 3.2σ (expected 4.2σ)**
- Measure best fit **μ=0.78 ± 0.27 at 125 GeV**
- **Mass measurement** 125.4 ± 0.5(stat.) ± 0.6(syst.) (Main systematics: energy scale (Z→ee), electron to photon extrapolation, linearity 45 GeV electrons => 60 GeV photons)



H→γγ cross-check: cut-based analysis

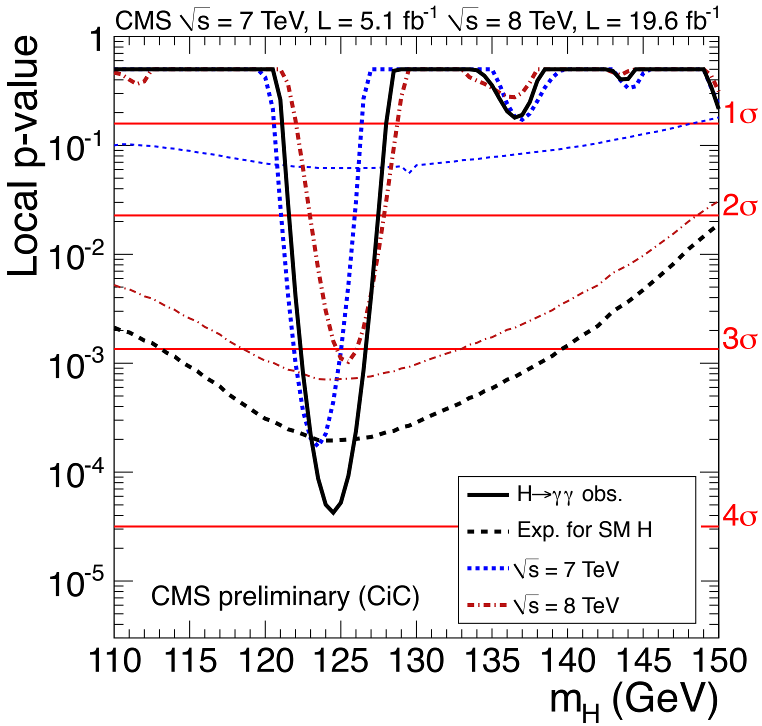
HIG-13-001





Cut-based:

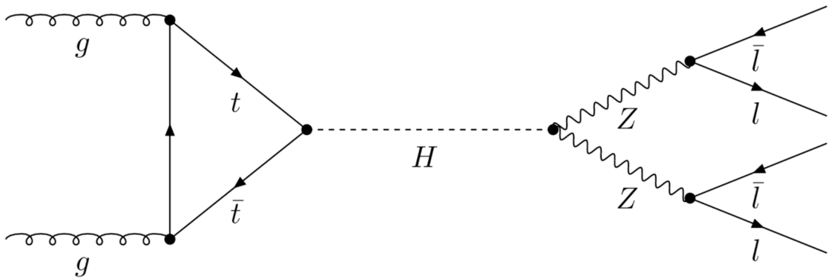
- **Observed local significance above 3.9σ (3.5σ expected)**
- Measure best fit **μ=1.11 ± 0.31 at 125 GeV**



	MVA analysis (at m_{H}=125 GeV)	cut-based analysis (at m_{H}=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

Compatibility of cut-based and MVA: within 1.5σ

H→ZZ→4l



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H
Z
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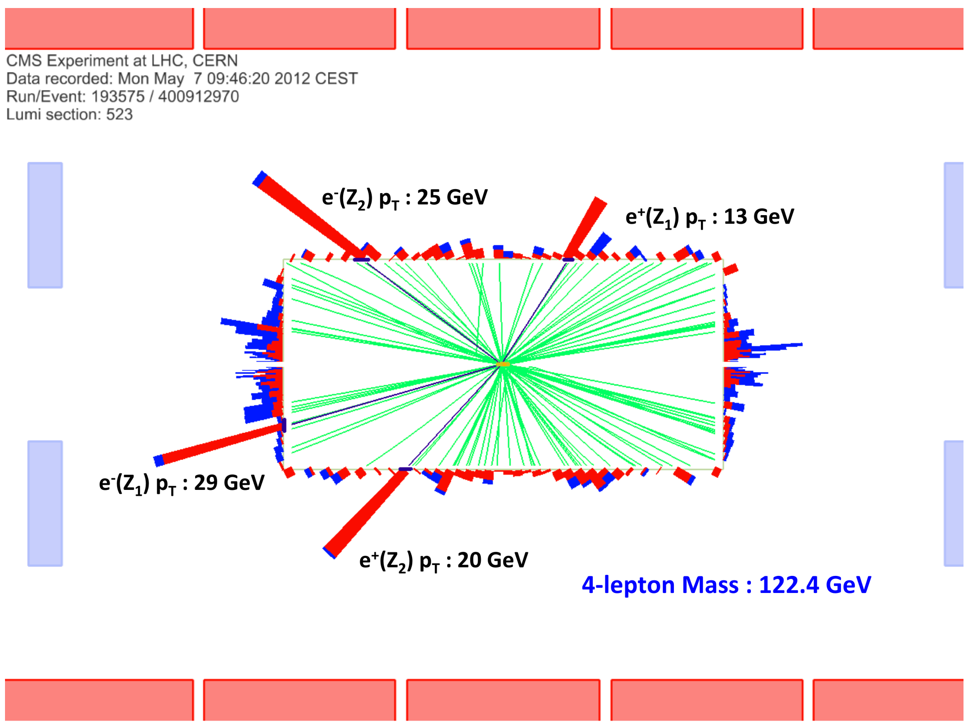
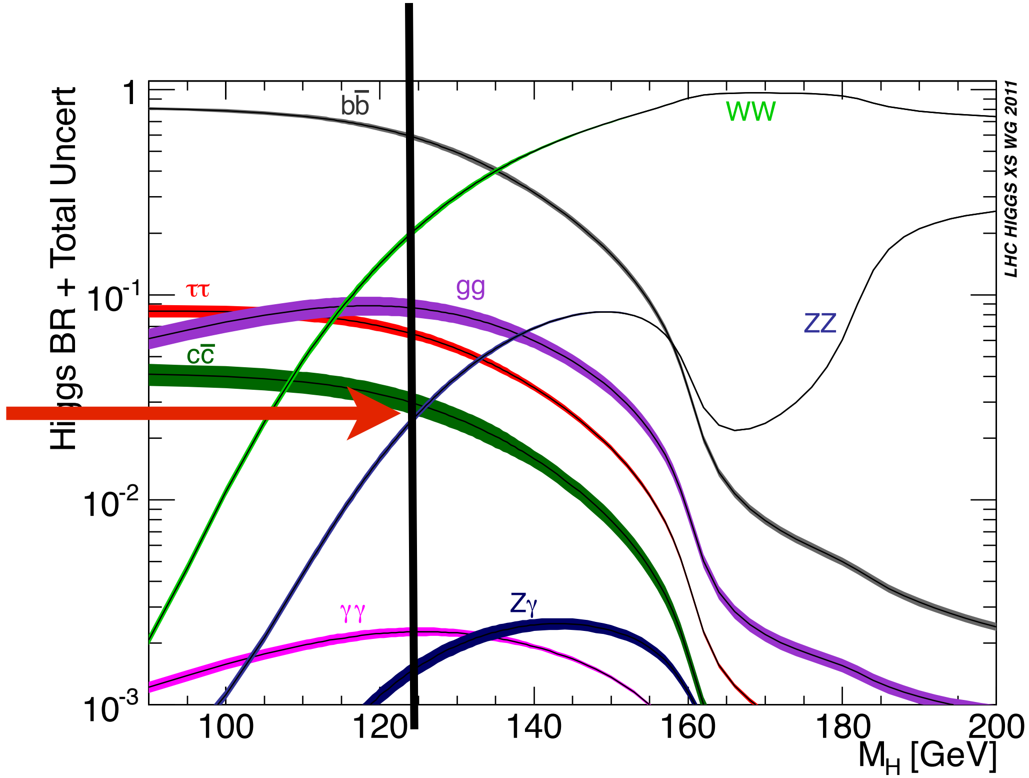


CMS Experiment at LHC, CERN
Data recorded: Mon May 7 09:46:20 2012 CEST
Run/Event: 193575 / 400912970
Lumi section: 523
e-(Z2) pT : 25 GeV
e+(Z1) pT : 13 GeV
e-(Z1) pT : 29 GeV
e+(Z2) pT : 20 GeV
4-lepton Mass : 122.4 GeV



Higgs BR + Total Uncert
LHC HIGGS XS WG 2011
bb̄
WW
ττ
gg
cc̄
ZZ
γγ
Zγ
1
10-1
10-2
10-3
100
120
140
160
180
200
MH [GeV]

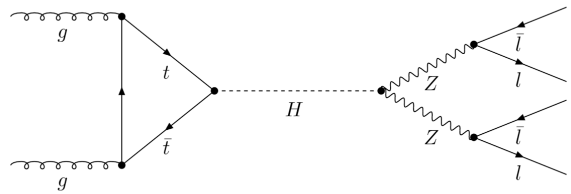
H→ZZ→4l analysis

arxiv:1312.5353

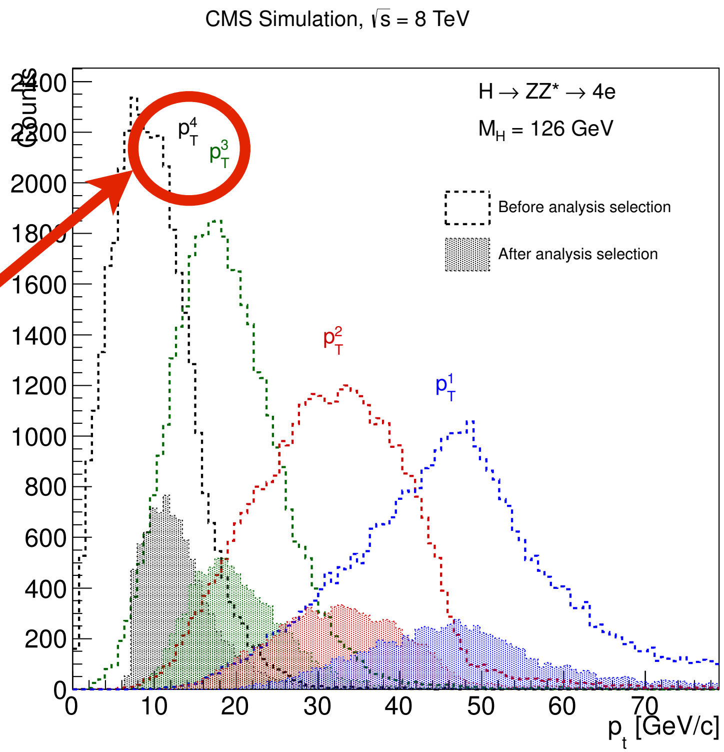
Run I legacy analysis

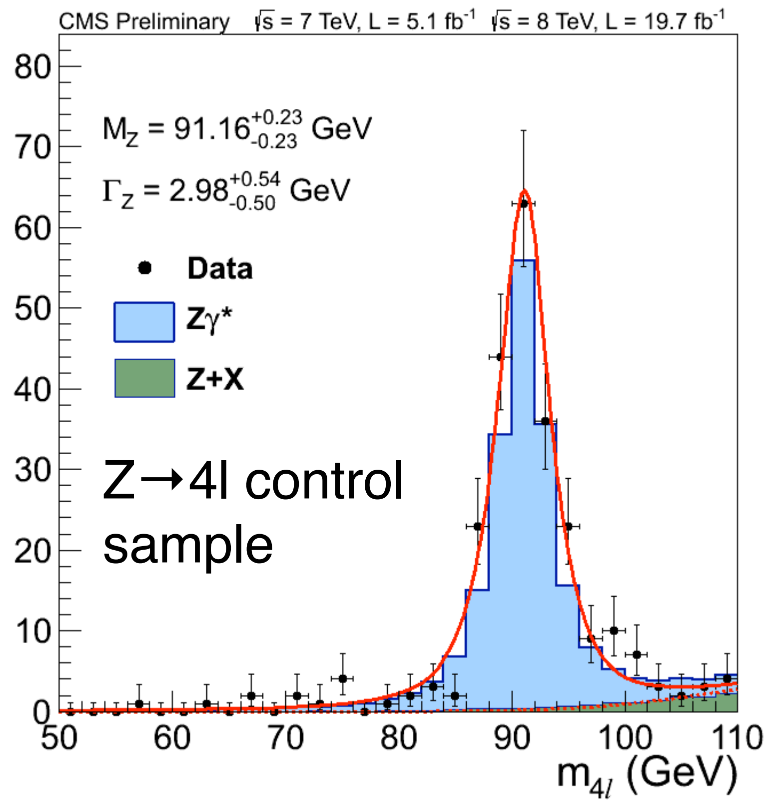
H→ZZ→4l analysis:

- **Very good s/b~2** (at 125 GeV).
- Main **backgrounds**: ZZ, Z+jets, ttbar
- Select four isolated leptons from the same vertex
- **Excellent mass resolution: 1-2%**
- 2l2τ channel included for higher mass



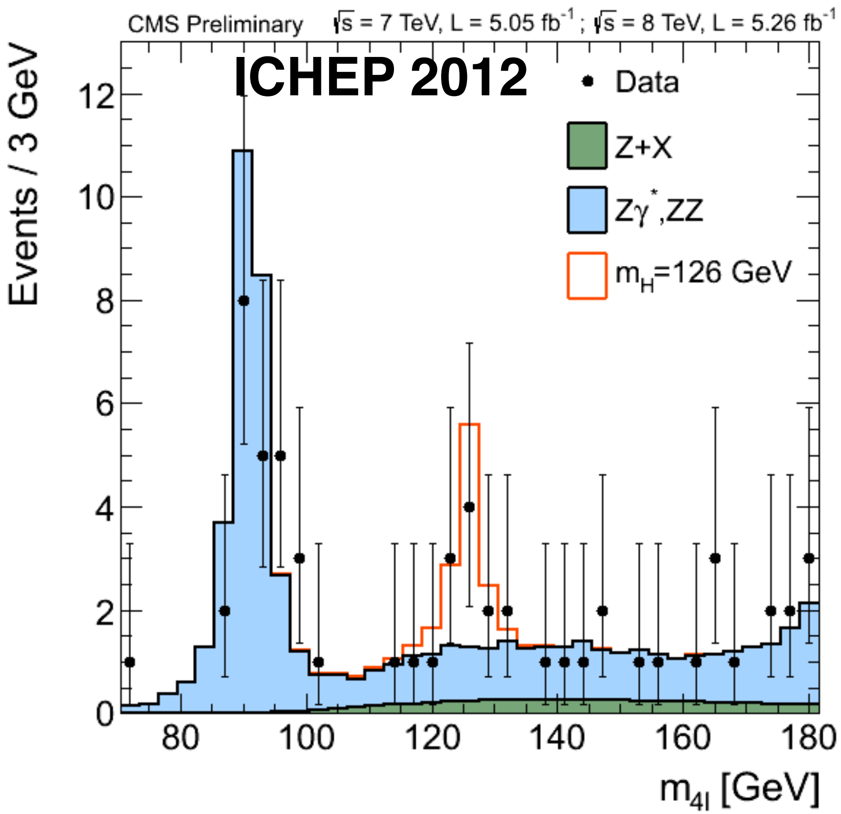
- Need **momentum** as **low** as pT>7 GeV (electrons) and pT>5 GeV (muons) to not loose too much **efficiency** missing the 4th lepton



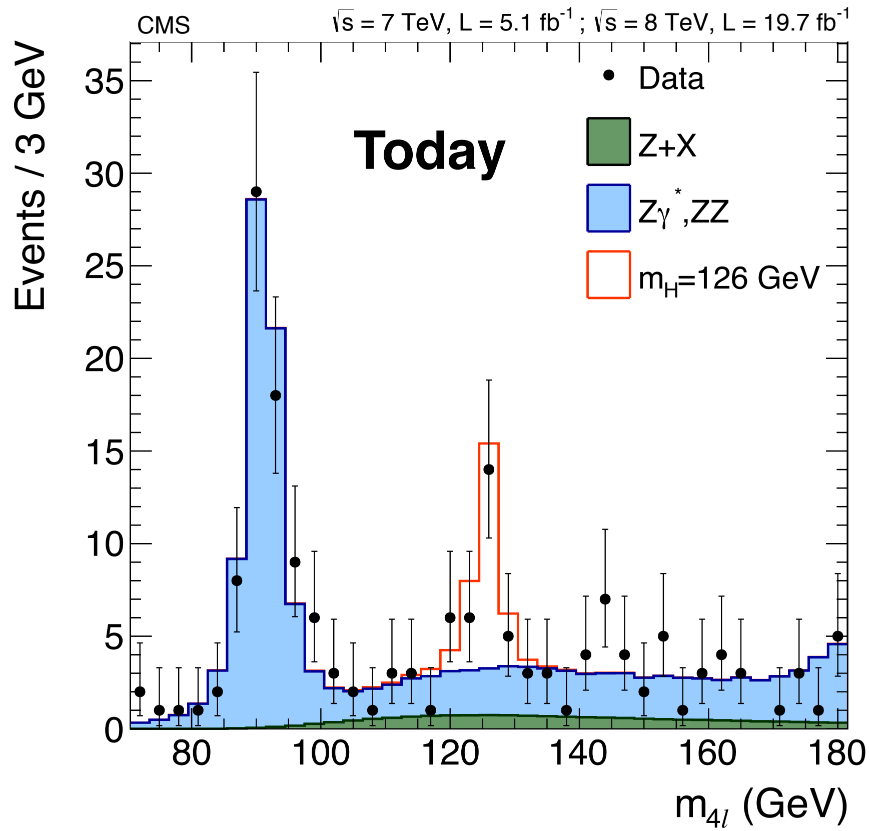


H→ZZ→4l analysis

arxiv:1312.5353



Note the scale!



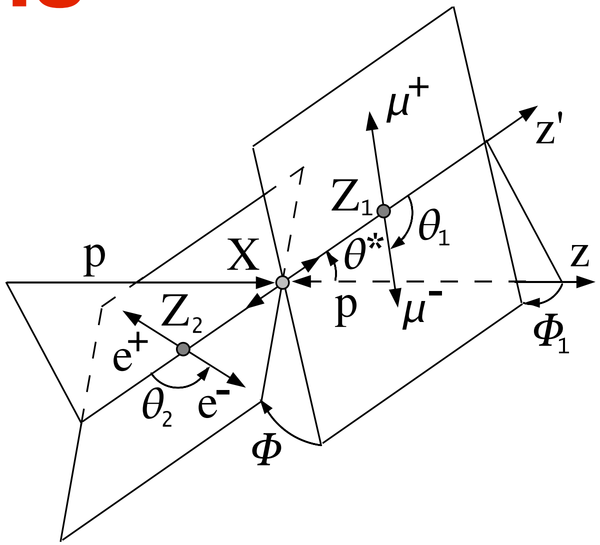
- **Small background (s/b~2), almost flat around 125 GeV**
- **Clear excess observed**

Mass range 121.5 - 130.5 GeV:

Channel	4e	$2e2\mu$	4μ	4ℓ
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
$Z + X$ background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
$m_H = 125$ GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
$m_H = 126$ GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

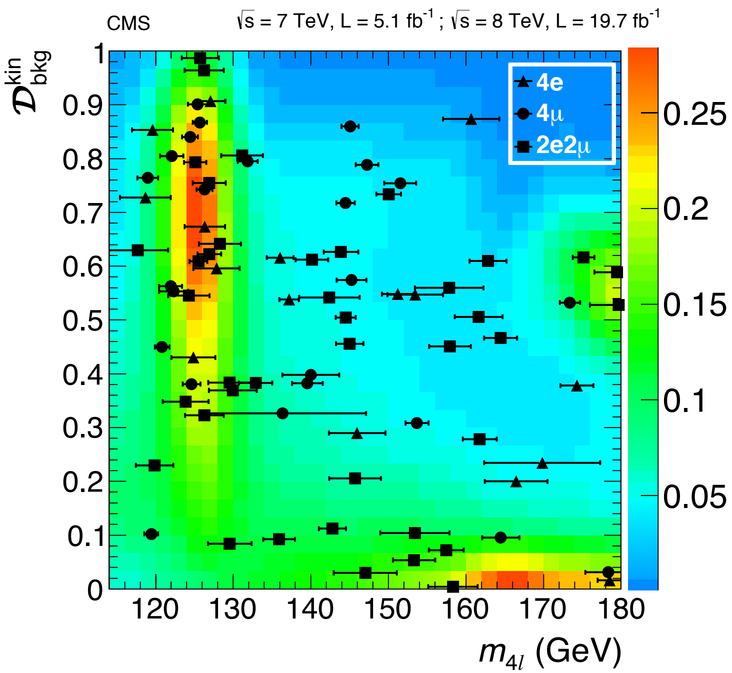
H→ZZ→4l analysis

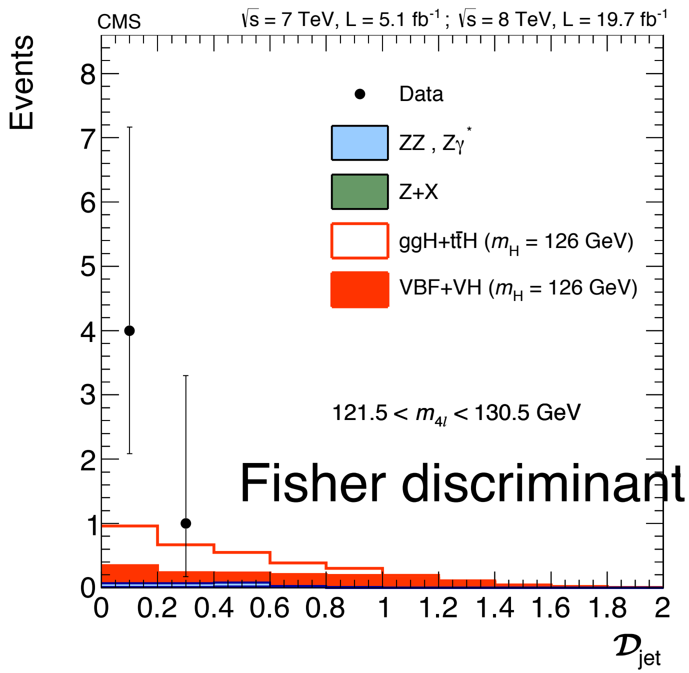
arxiv:1312.5353



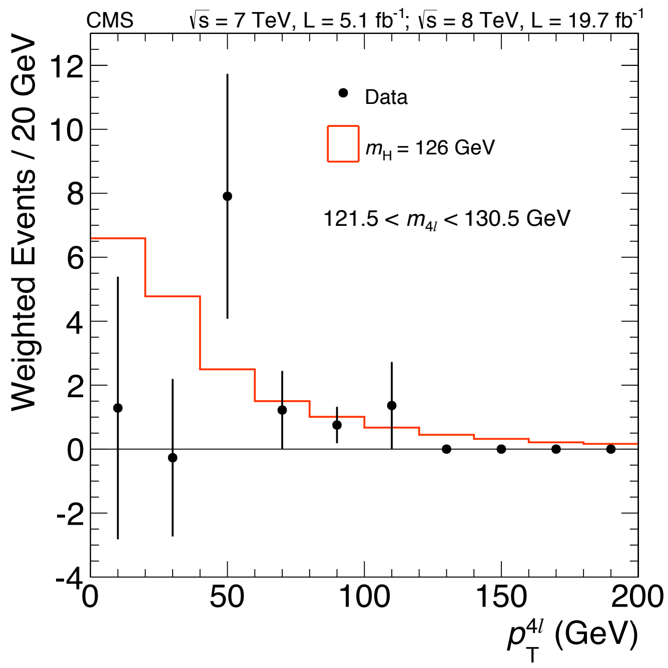
- **0,1jet Kinematic discriminant:** Matrix element method using invariant mass of Z1 and Z2 and 5 angular variables.
- **2-jets:** Fischer discriminant with jet information
- **3D analysis** in Mass, KD, and pT(H) (**untagged**), and Mass, KD, Fischer discriminant (**dijet tag**)
- Start to **measure Higgs differential distributions: Higgs pT** using s-plot method

KD in Signal MC





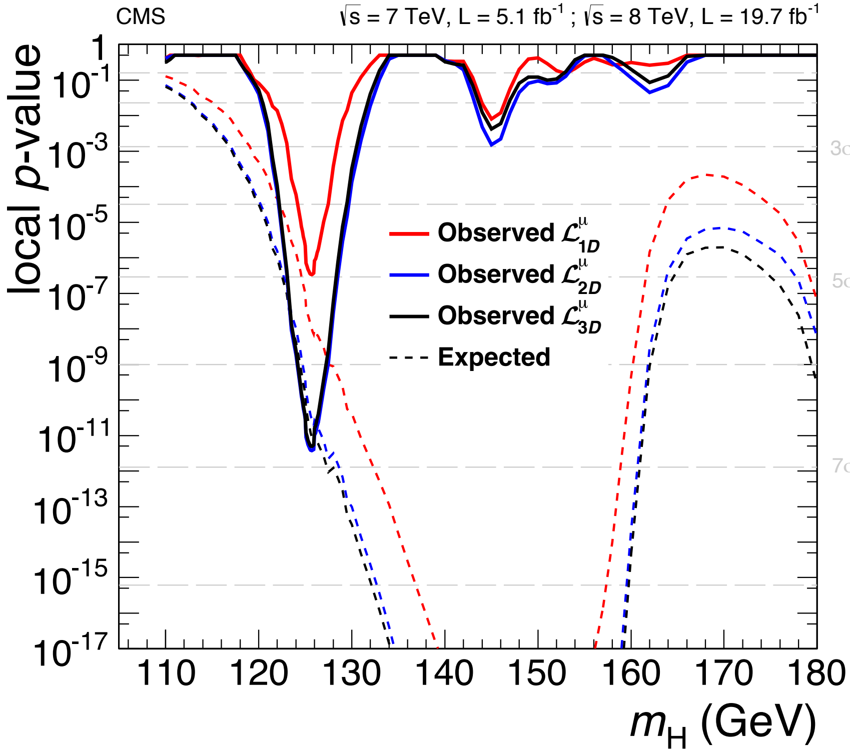
Fisher discriminant

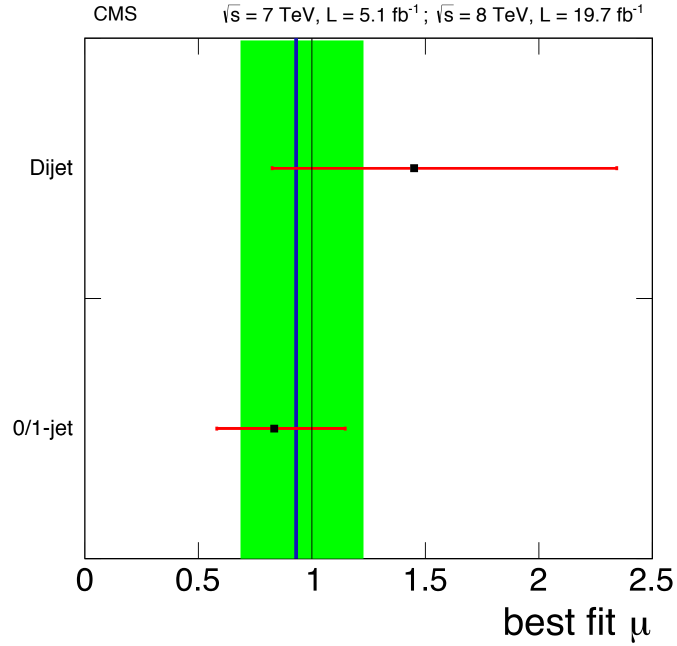


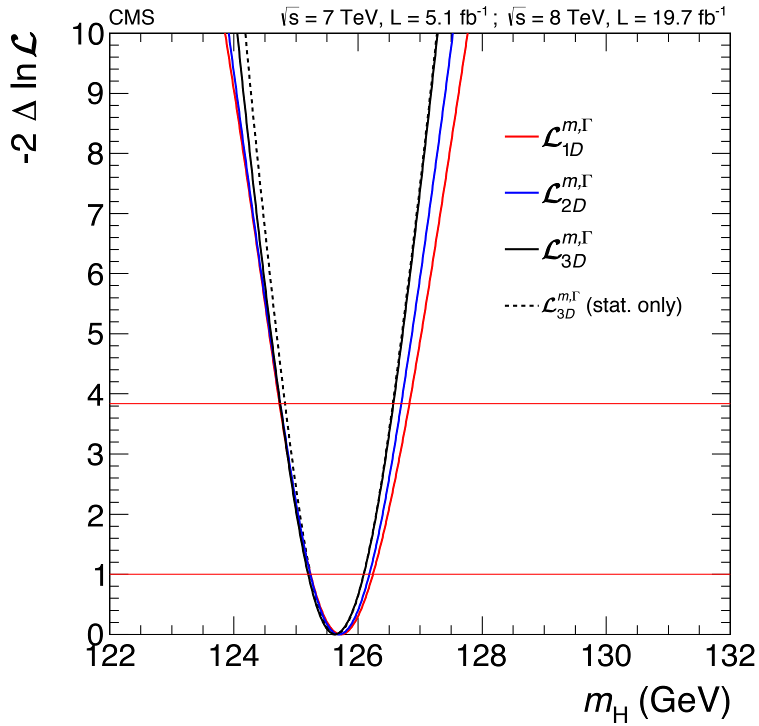
Higgs pT with s-plot method

H→ZZ→4l results

arxiv:1312.5353



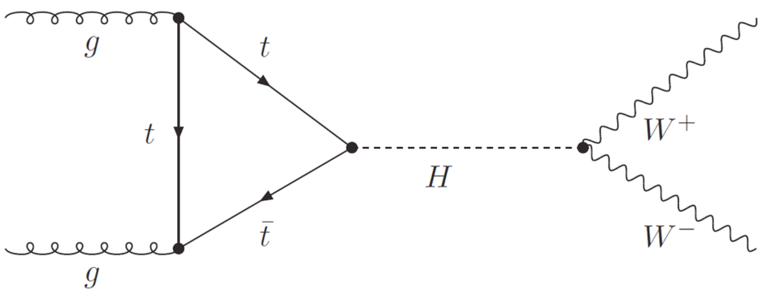


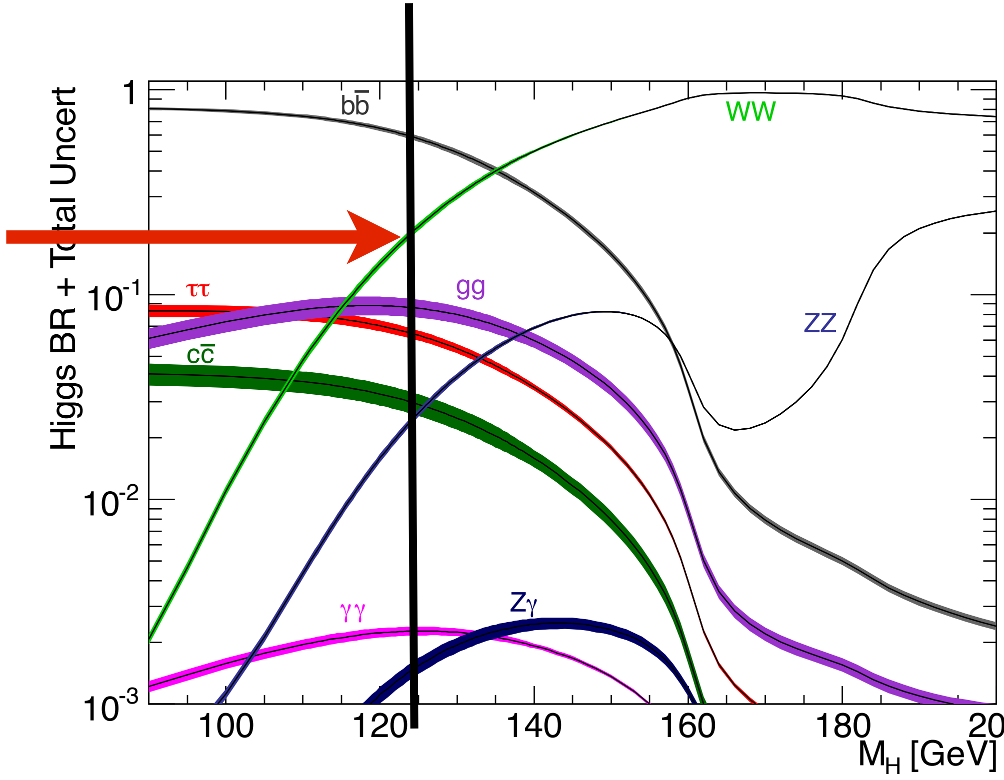


- **Observed significance 6.8σ**
- Measure best fit at 125.7 GeV
  $\mu=0.93^{+0.26}_{-0.23}$ (stat.)$\pm^{+0.13}_{-0.09}$ (syst.)

- **Mass measurement** with 3D fit **(m_{4l}, δm_{4l}, KD)**
- **m=125.6 ± 0.4 (stat) ±0.2 (syst) GeV**

H→WW


g
t
t
$\bar{t}$
g
H
W^+
W^-


Higgs BR + Total Uncert
LHC HIGGS XS WG 2011
bb̄
WW
ττ
gg
cc̄
ZZ
γγ
Zγ
1
10^{-1}
10^{-2}
10^{-3}
100
120
140
160
180
200
M_H [GeV]

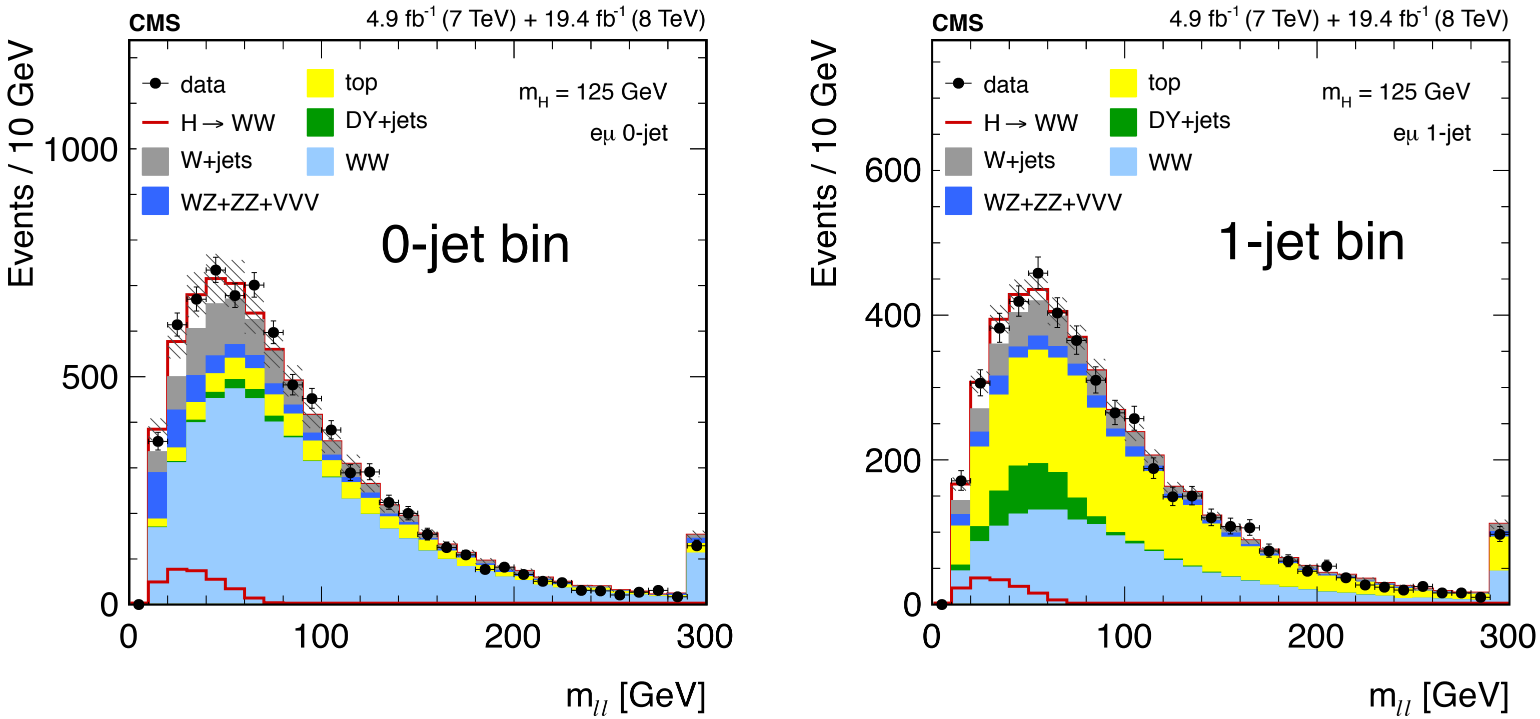
H→W⁺W⁻ analysis

arxiv:1312.1129

Run I legacy analysis

H→WW→2l2v analysis:

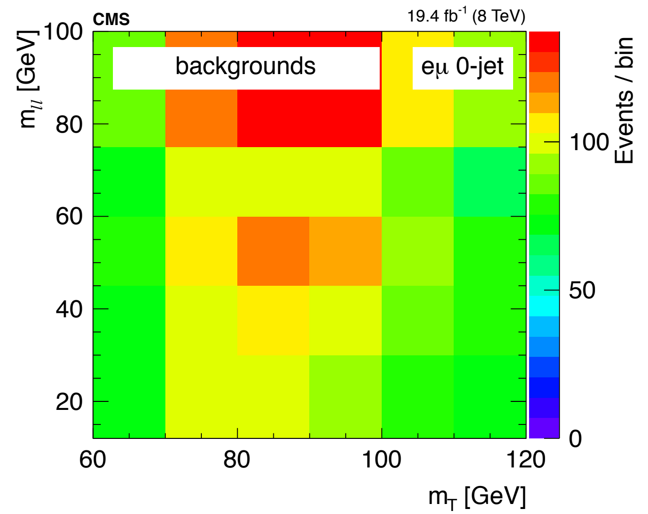
- **High BR, but no mass peak (resolution is ~20%)**
- Select two isolated leptons with pT>20,10 GeV and mET>20 GeV
- Categorize in **0-jet, 1-jet, 2-jet bins**, then **ee,μμ,eμ** with opposite charge
- Main backgrounds: WW, top (1,2jet bins), W+jets (estimated from control regions in data)

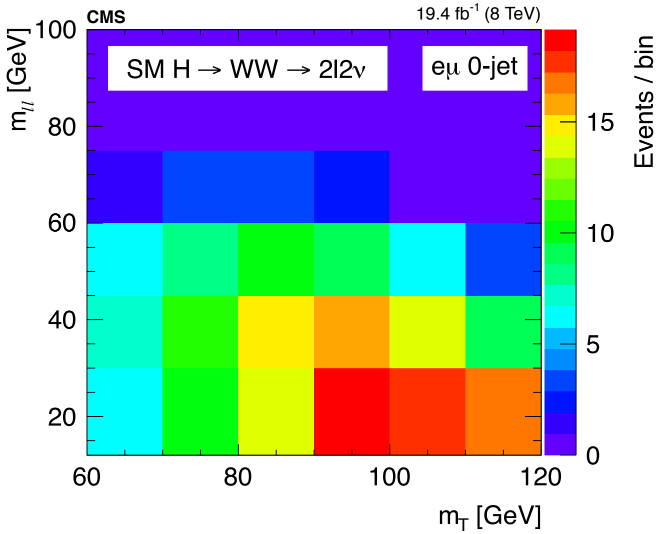


H→W⁺W⁻ analysis

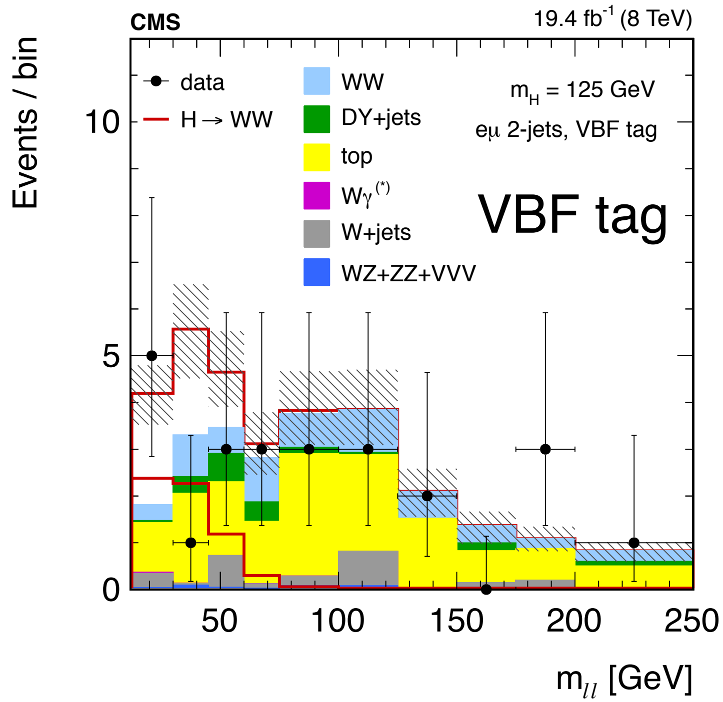
arxiv:1312.1129

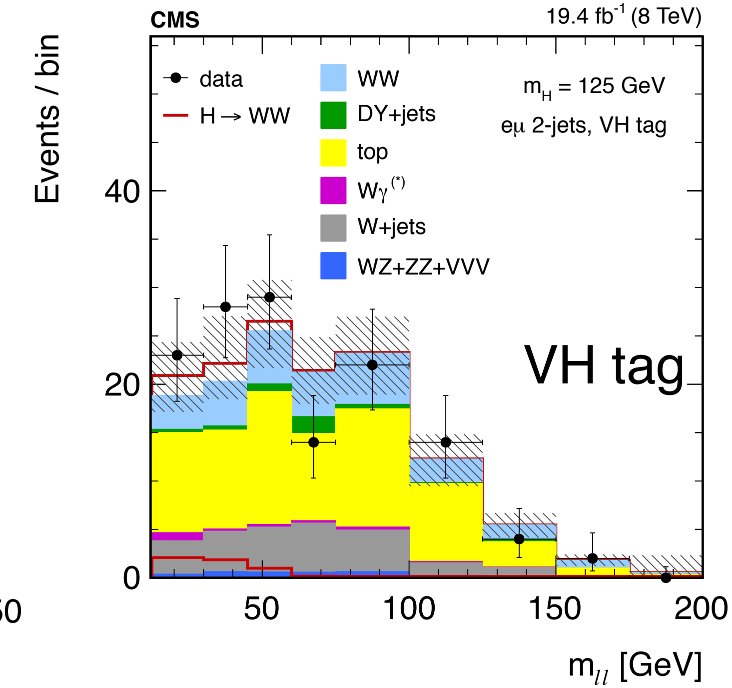
2D analysis in **(m_T, m_{ll})** for the opposite flavor 0-jet and 1-jet bins (cross-check with a 2nd 2D analysis)





2jets: VBF-tag and VH tag use a fit to mll distribution

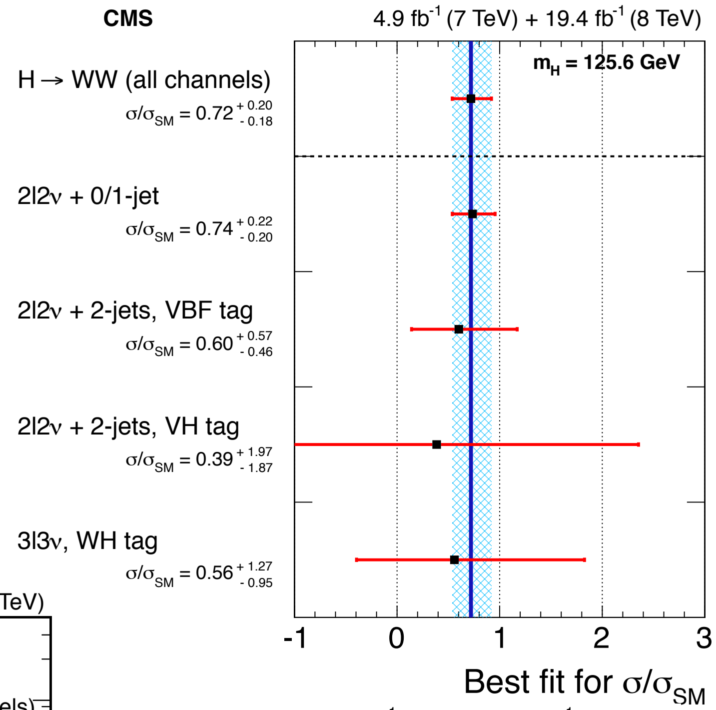




Trilepton final state also used:
WH→3l3ν, ZH→3lν+2jets

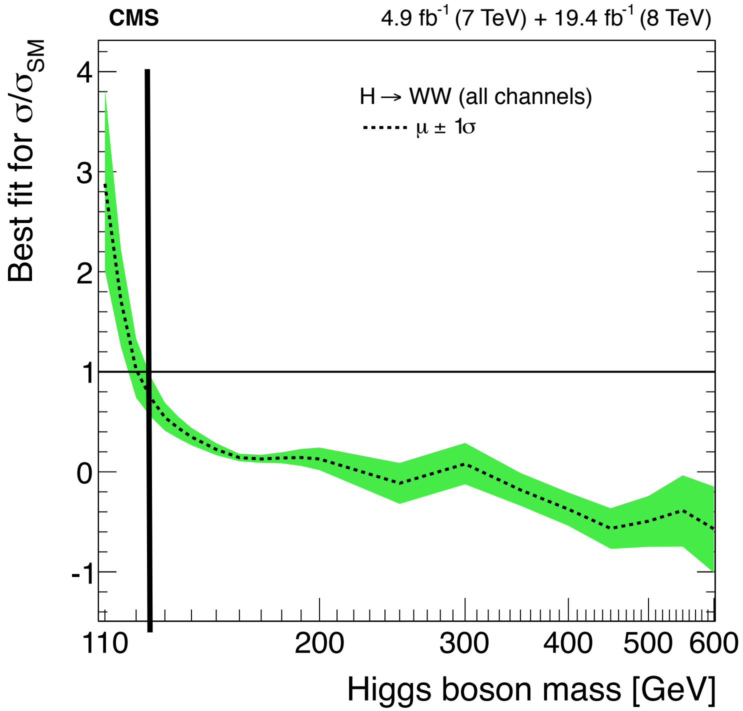
H→W+W- analysis

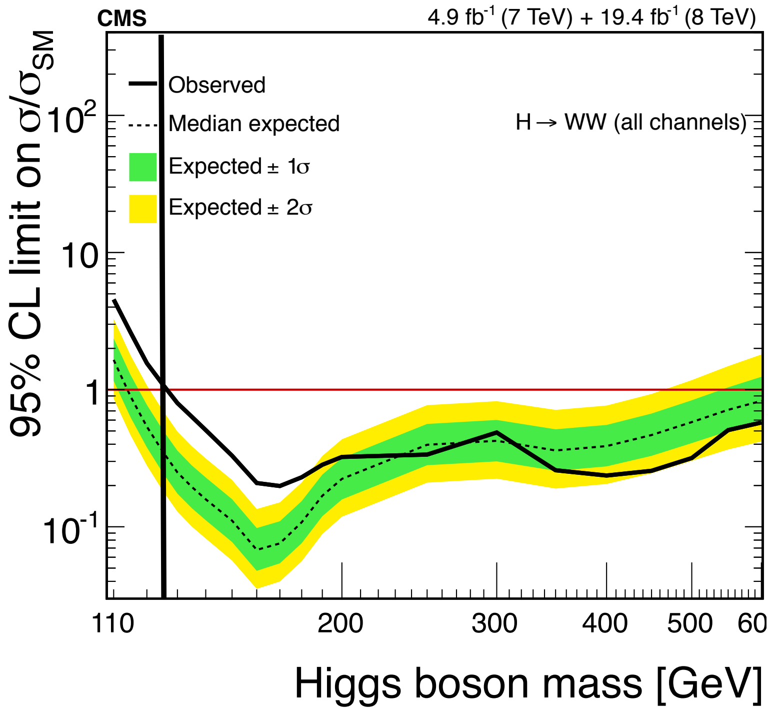
arxiv:1312.1129

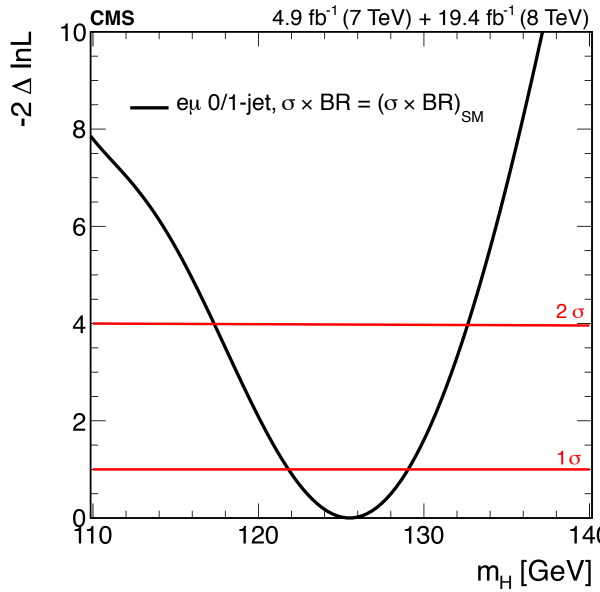


Broad excess observed in exclusion limits compatible with presence of signal

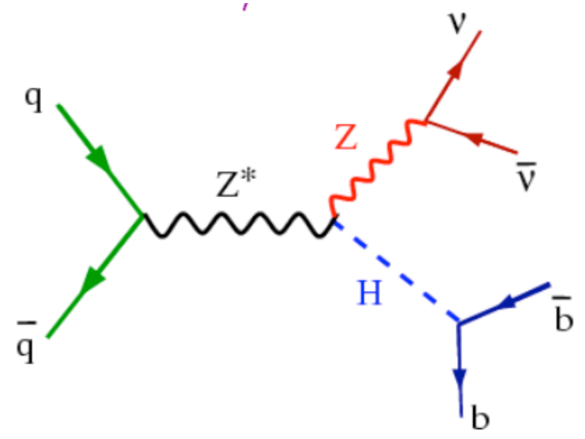
- **Best fit** signal strength **$\mu=0.72^{+0.20}_{-0.18}$ at 125.6 GeV**
- **Local significance: expected 5.8σ, observed 4.3σ**
- **Mass measurement: $128.2^{+6.6}_{-5.3}$ GeV**

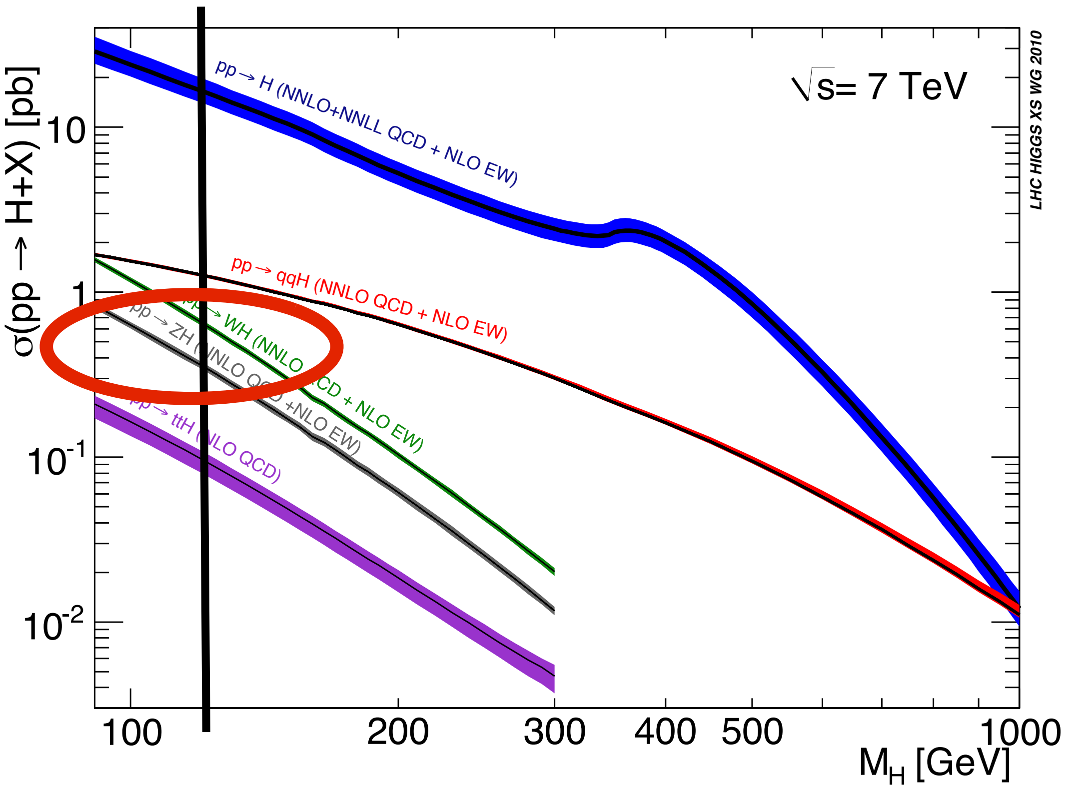


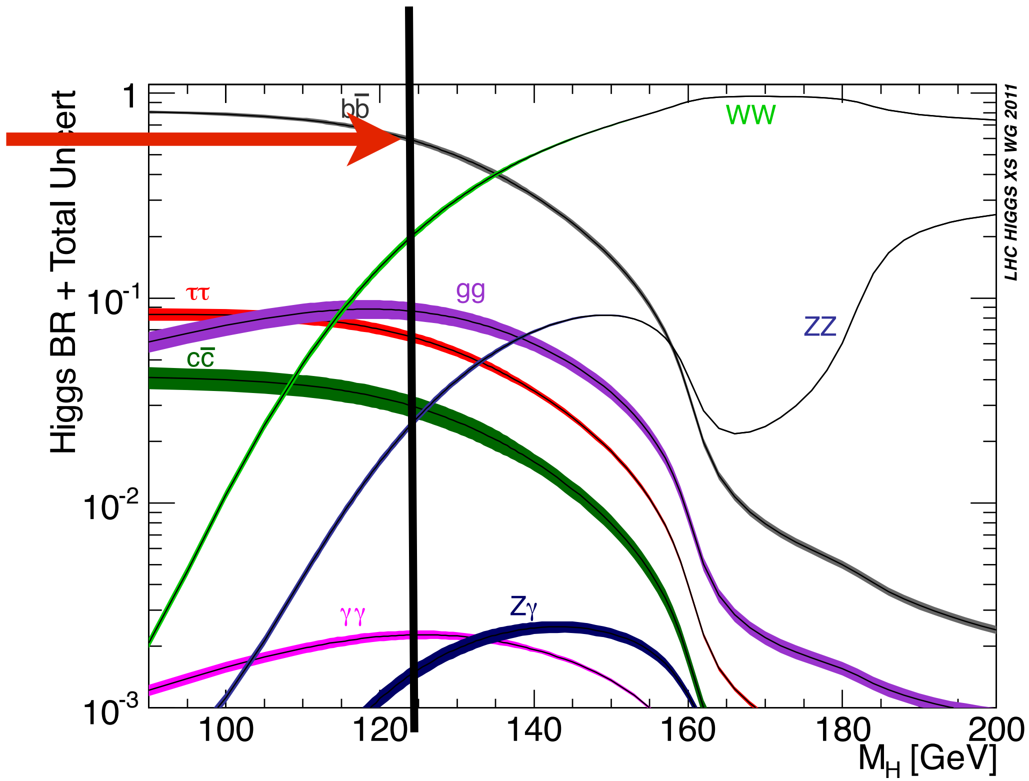




$H \to b\bar{b}$


q
$\bar{q}$
Z*
Z
ν
$\bar{\nu}$
H
$\bar{b}$
b


√s= 7 TeV
LHC HIGGS XS WG 2010
σ(pp → H+X) [pb]
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
M_H [GeV]

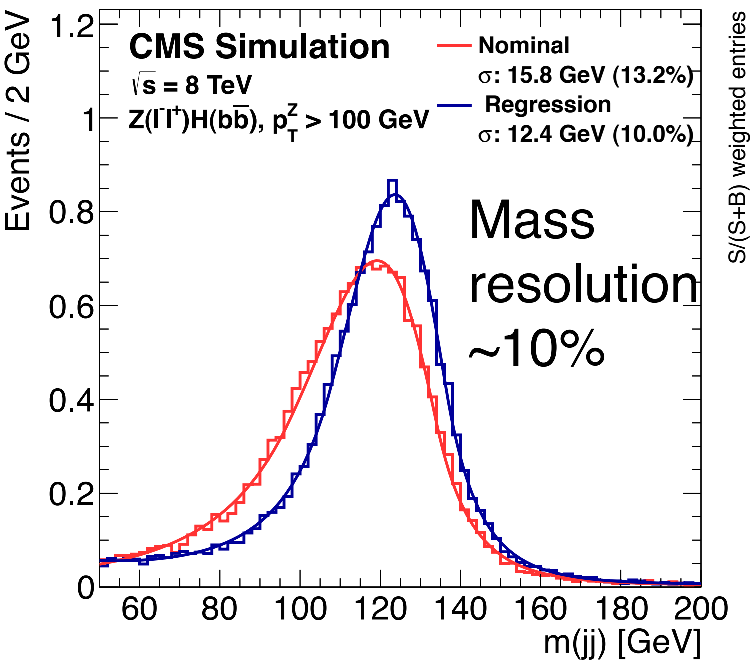

Higgs BR + Total Uncert
LHC HIGGS XS WG 2011
$b\bar{b}$
WW
ττ
gg
$c\bar{c}$
ZZ
γγ
Zγ
M_H [GeV]

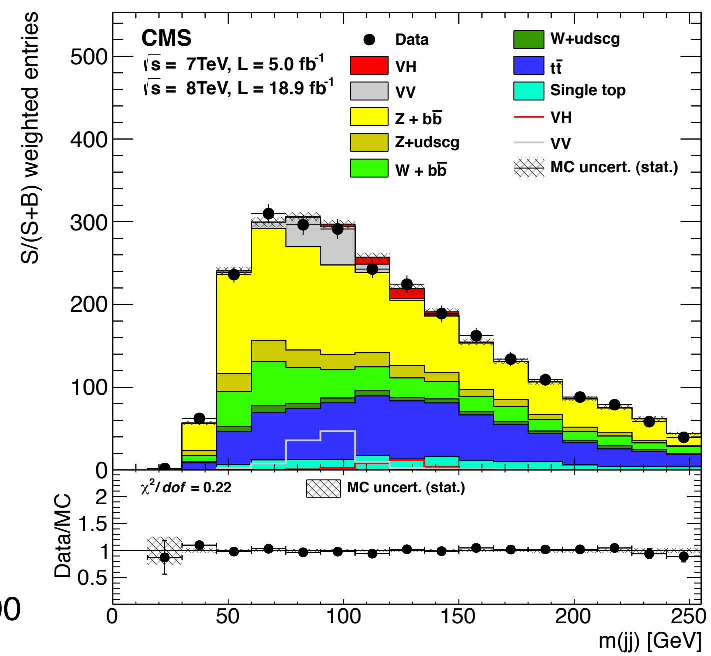
H→b$\bar{b}$ analysis

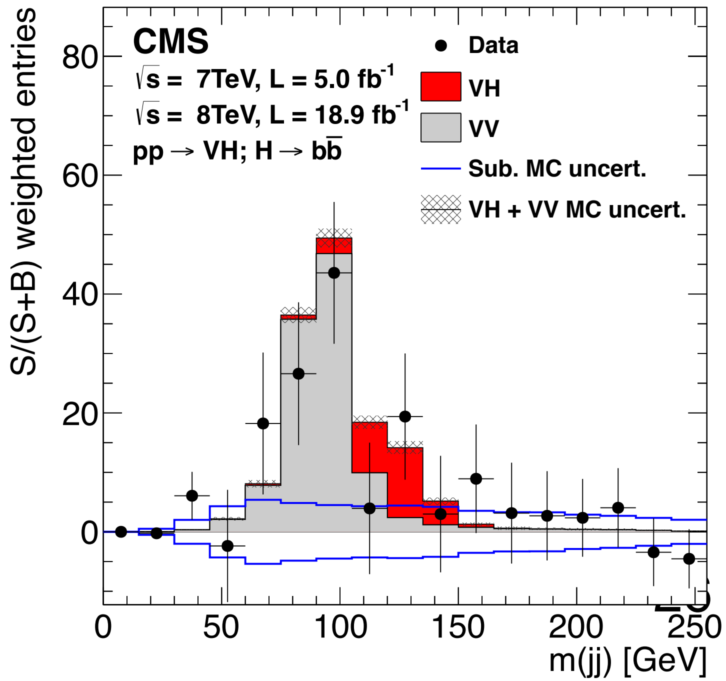
arxiv:1310.3687

Run I legacy analysis

- **Large branching ratio, but large QCD background.**
- Improve s/b by requiring two central **b-tagged jets**
- **Require associated production: VH(bb) with V being W(ev), W(μv), Z(ee), Z(μμ), Z(vv)**
- Trigger on the associated vector boson: single/double lepton, mET(+jets)
- **Categorize** according to **vector boson pT** (170 GeV but for Z(ll), 100 GeV)
- **b-jet energy regression** using 2nd vertex and jet properties, mET direction and soft lepton info inside the jet => improves analysis sensitivity by 15-20%







$H \to b\bar{b}$: BDT shape analysis

arxiv:1310.3687

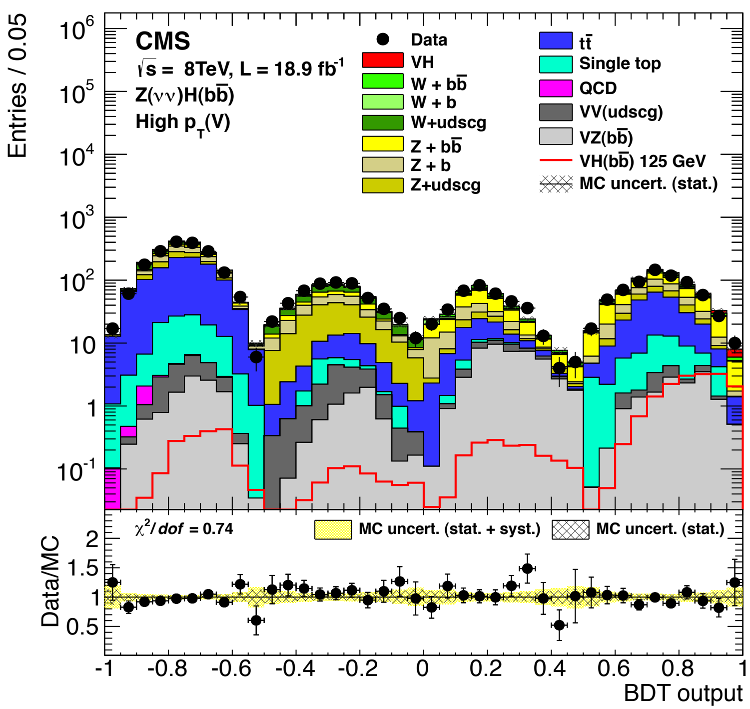
- Main background after preselection: V+2jets, VV, top

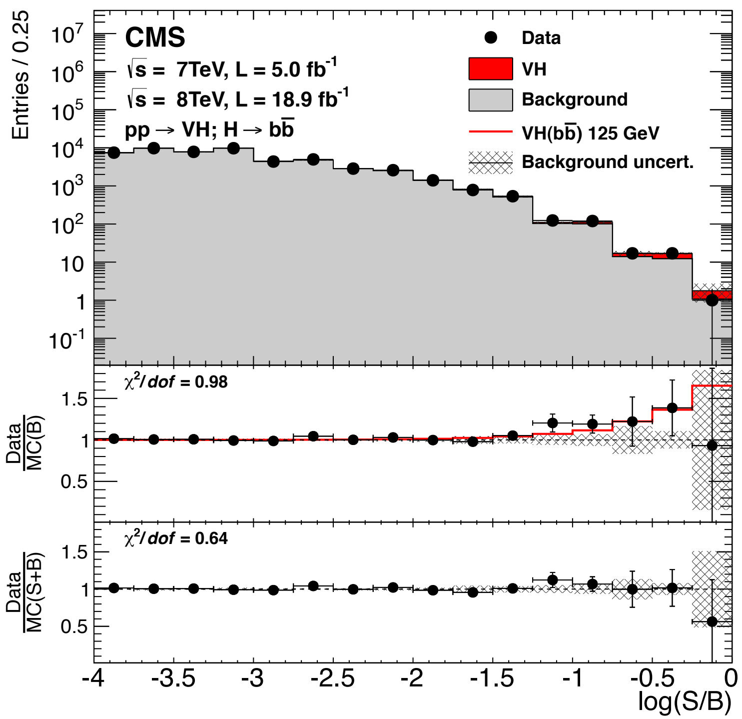
BDT shape analysis:

- BDT **variables**: mainly jets and vector boson kinematics, b-tagging discriminant
- Fit to the **BDT shapes** in each channel (10% improvement wrt cut and count)

- **4 "staggered" BDT**, trained against diboson, ttbar, W/Z+jets, and all background

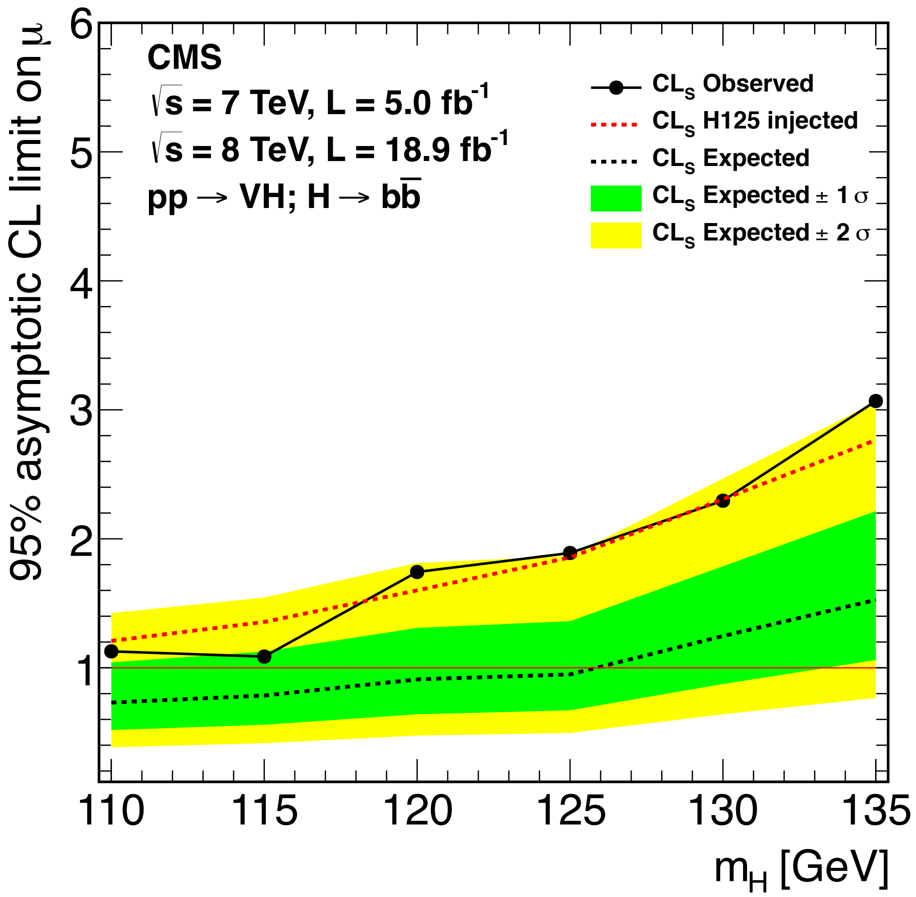
- Check that such a BDT approach is able to **measure VZ(bb)**: 6.9σ

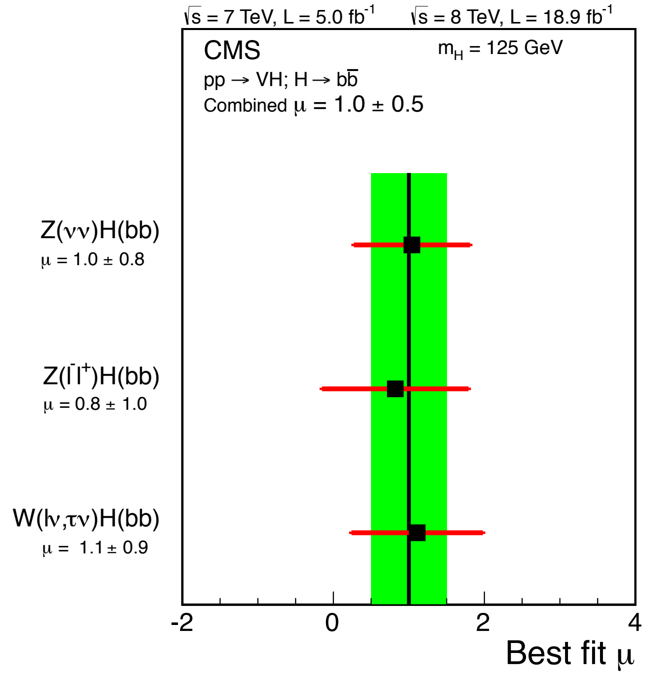


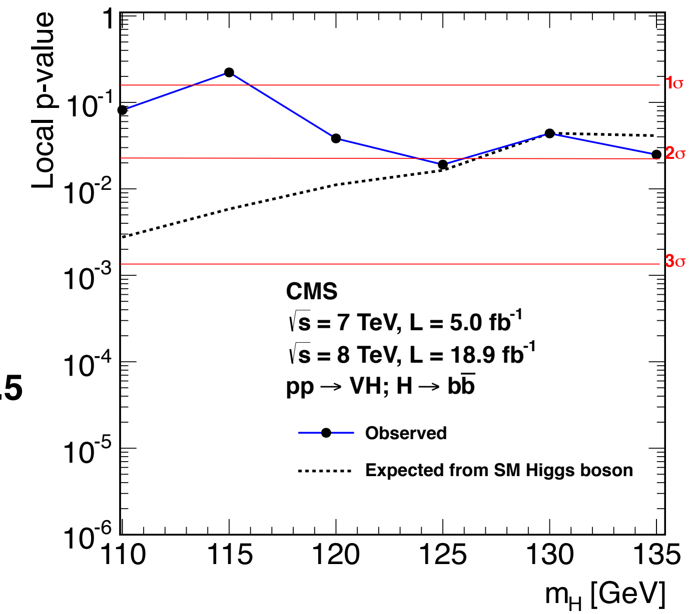


$H \rightarrow b\bar{b}$ results

arxiv:1310.3687



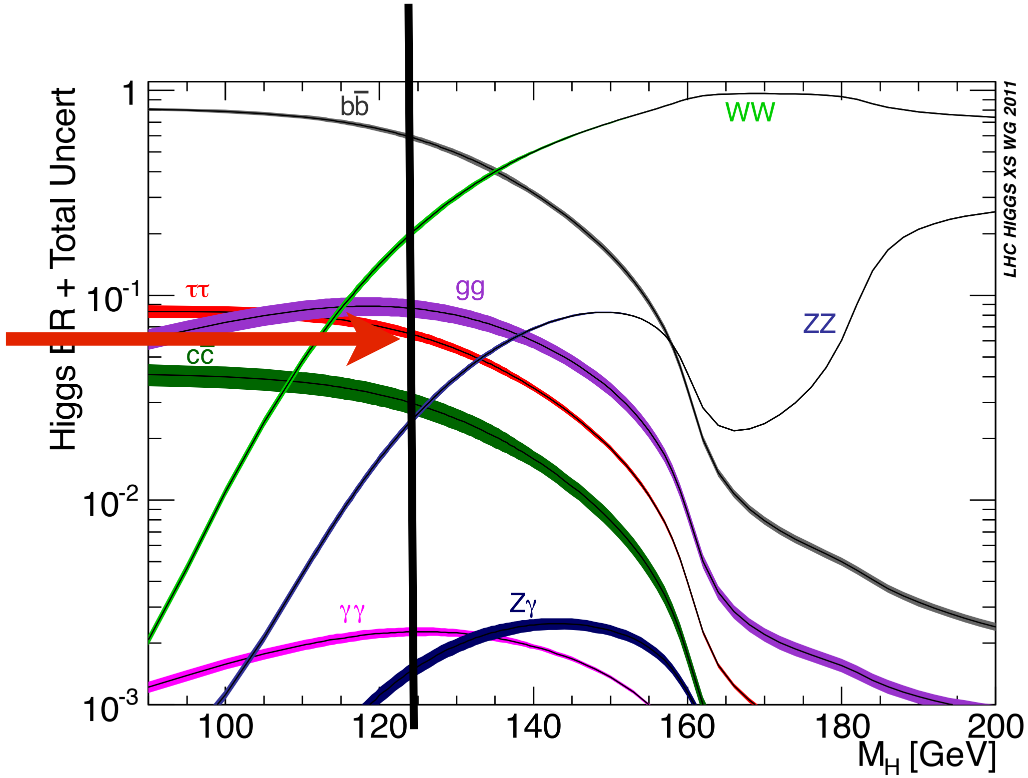




-Broad excess compatible with SM Higgs injection

- At 125 GeV, observed **p-value 2.1σ** Best fit **$\mu=1.0^{+0.5}_{-0.5}$**

H → τ⁺τ⁻



Higgs BR + Total Uncert
LHC HIGGS XS WG 2011
bb̄
WW
ττ
gg
cc̄
ZZ
γγ
Zγ
1
10⁻¹
10⁻²
10⁻³
100
120
140
160
180
200
M_H [GeV]

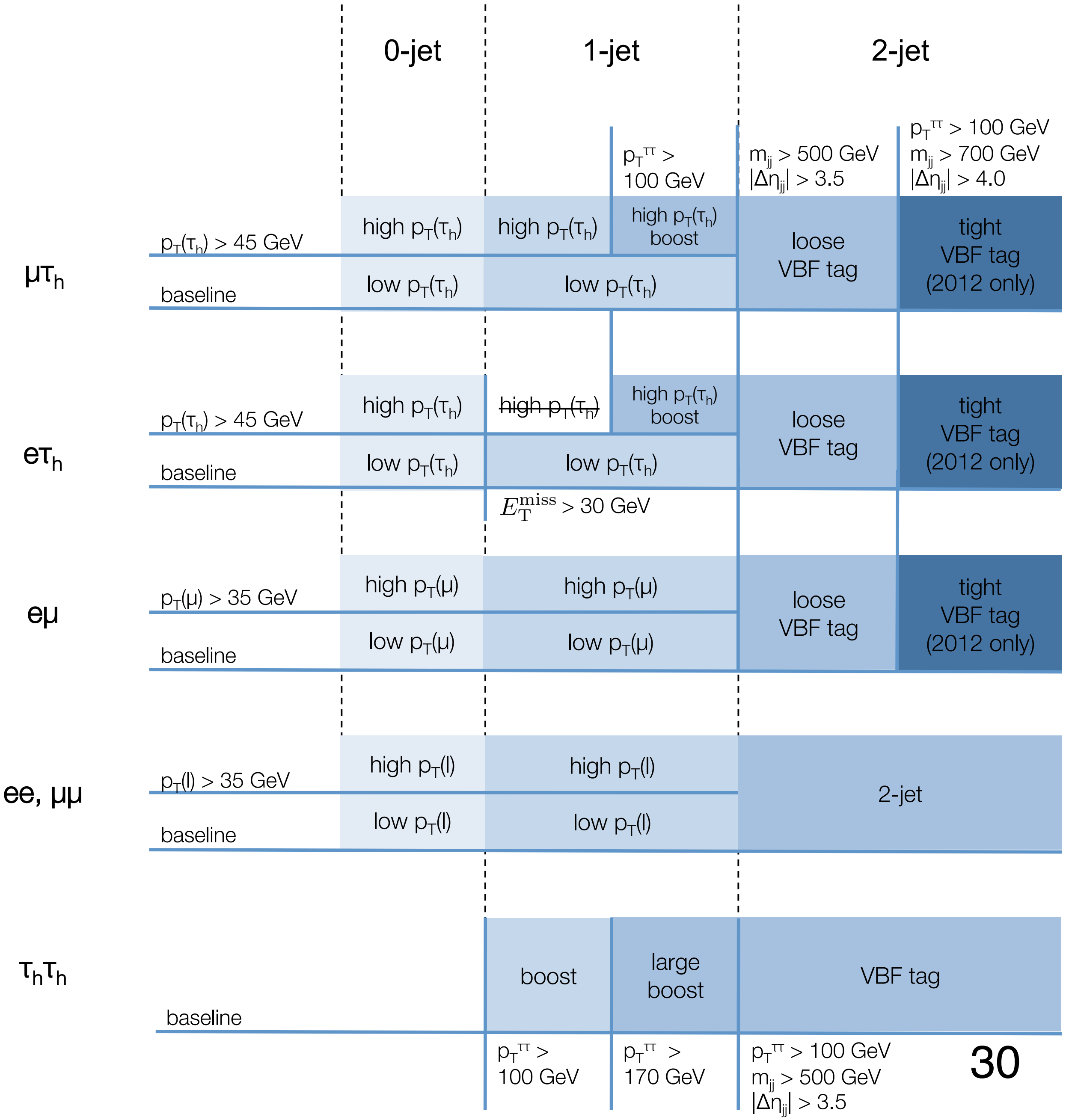
$H \rightarrow \tau^+\tau^-$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13004TWikiUpdate

New! (December)

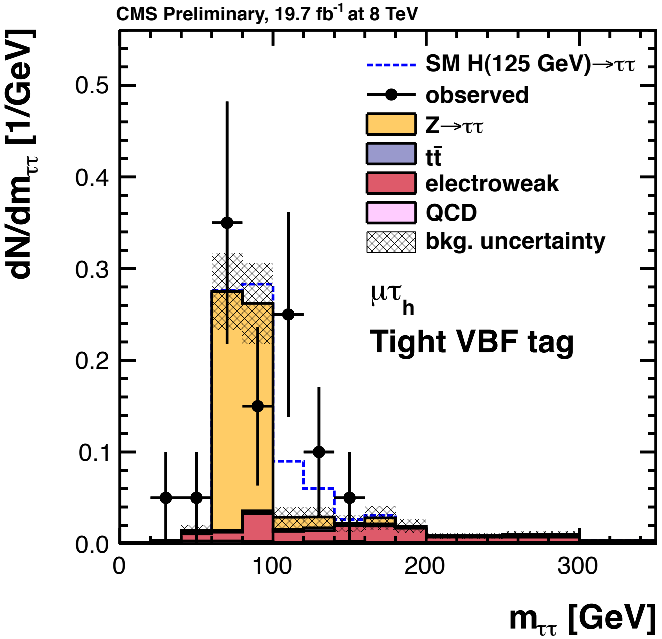
5 final states: $\mu\tau_h$, $e\tau_h$, $e\mu$, $\tau_h\tau_h$, $\mu\mu$, also associated production VH($\tau\tau$)

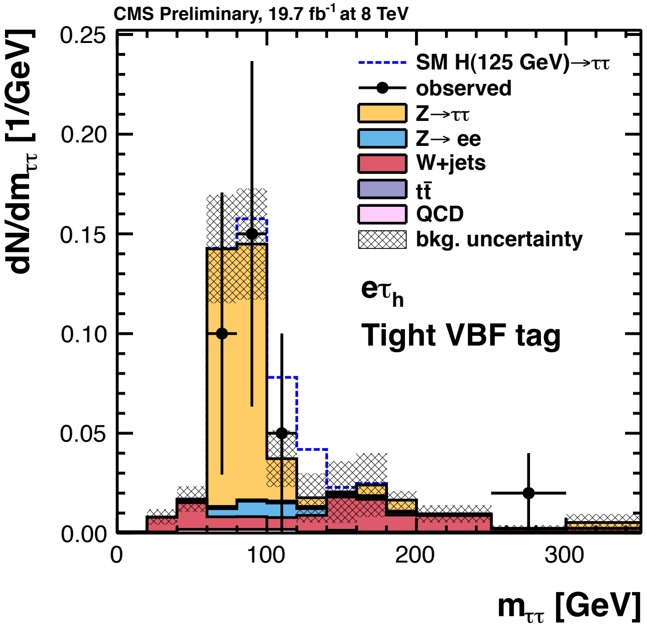
- Main background: QCD, Z($\tau\tau$)+jets
- **Tau reconstruction with the particle-flow (PF) algorithm**
- MVA for τ_h isolation in rings and for PF mET
- Mass reconstruction with matrix element method (SVFit)
- **Categories: 2-jet (VBF tag, most sensitive), 1-jet**, 0-jet
- **Split further categories with pT**
- Data-driven method to estimate tau fake rate from control regions

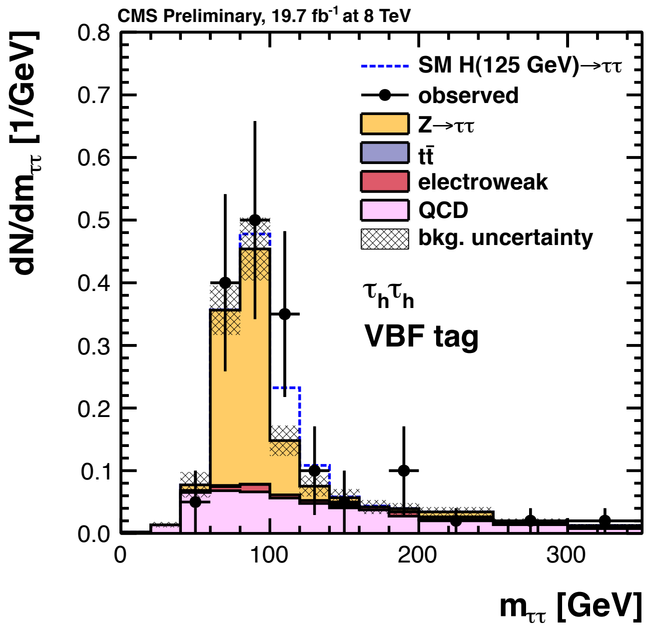


$H \to \tau^+\tau^-$

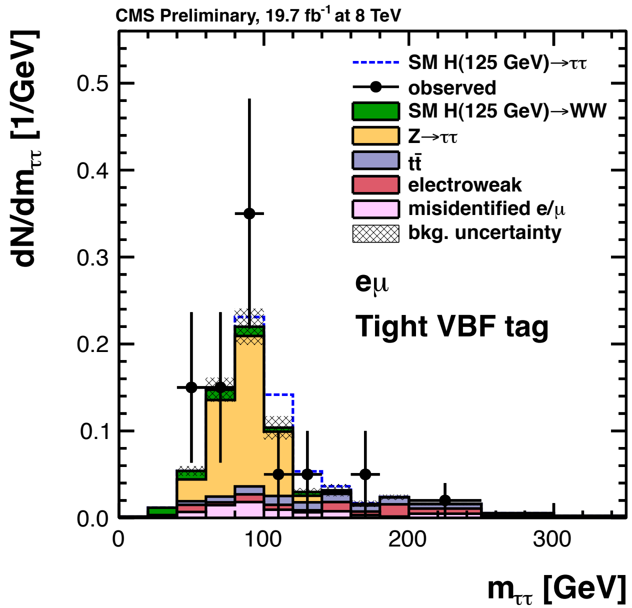
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13004TWikiUpdate





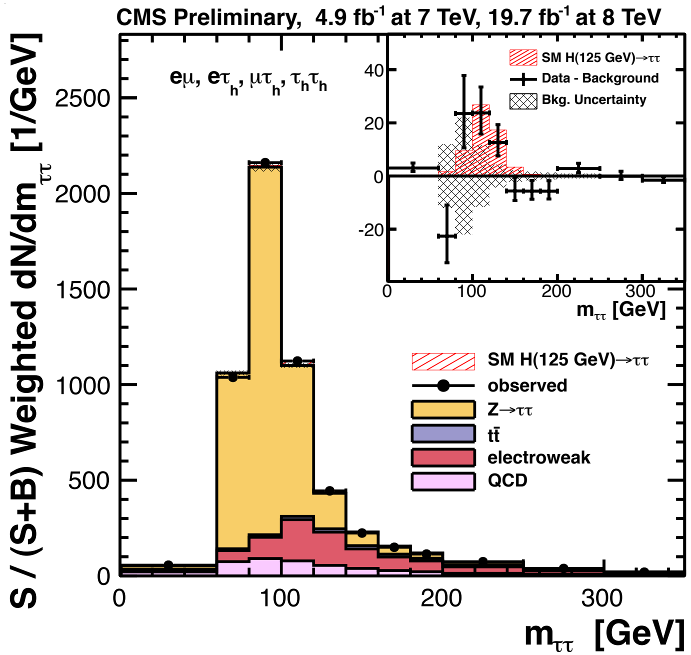


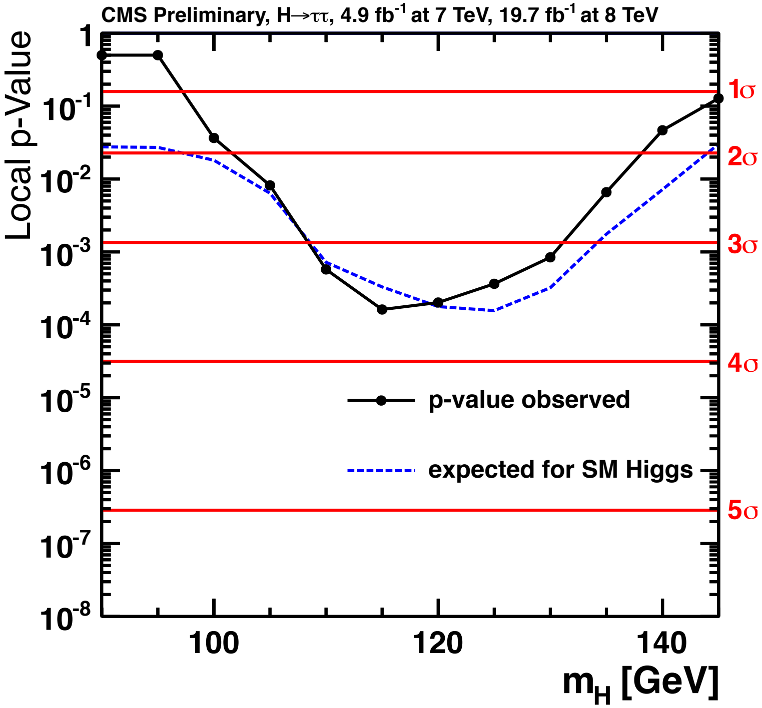
- Ditau invariant mass distributions in the VBF channel as an illustration (best sensitivity)
- 0-jet not used for sensitivity

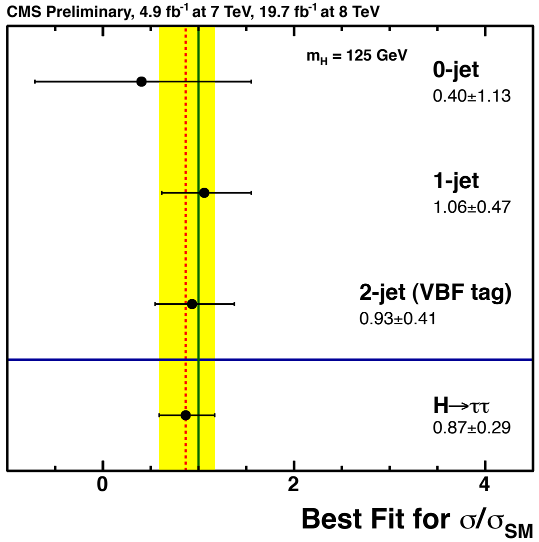


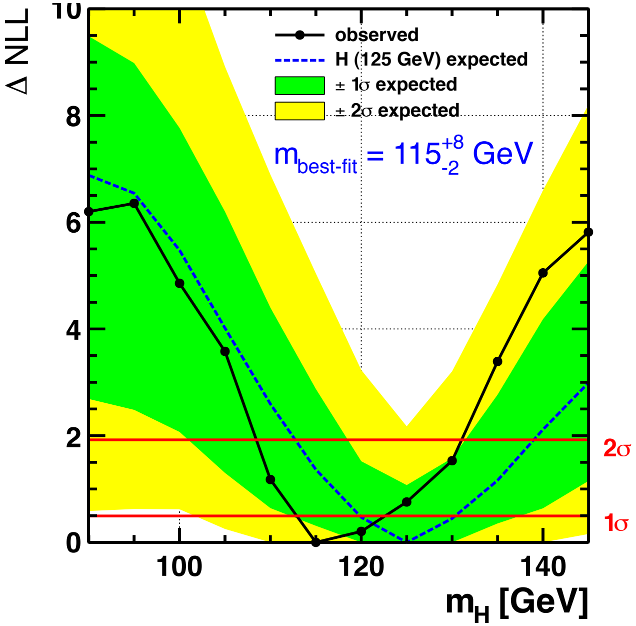
$H \rightarrow \tau^+\tau^-$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13004TWikiUpdate







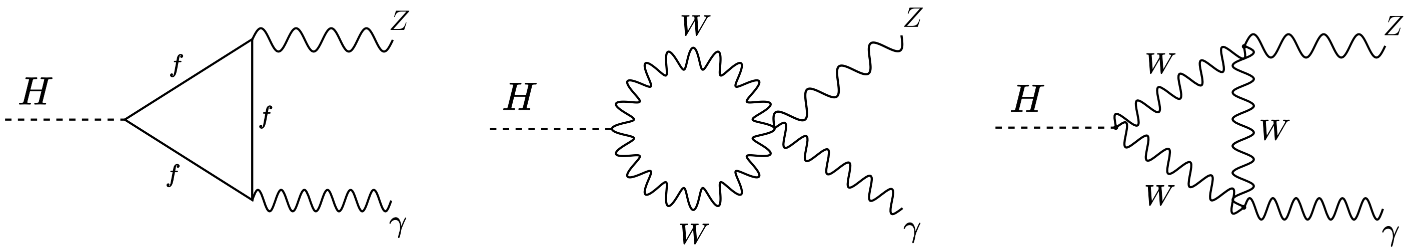


- **Broad excess observed compatible with the signal injection test**
- Local **p-value >3σ** in 110-130 GeV range
- Best fit **μ=0.87±0.29**
- **Mass: 115^{+8}_{-2} GeV**
- **Evidence for coupling to tau**

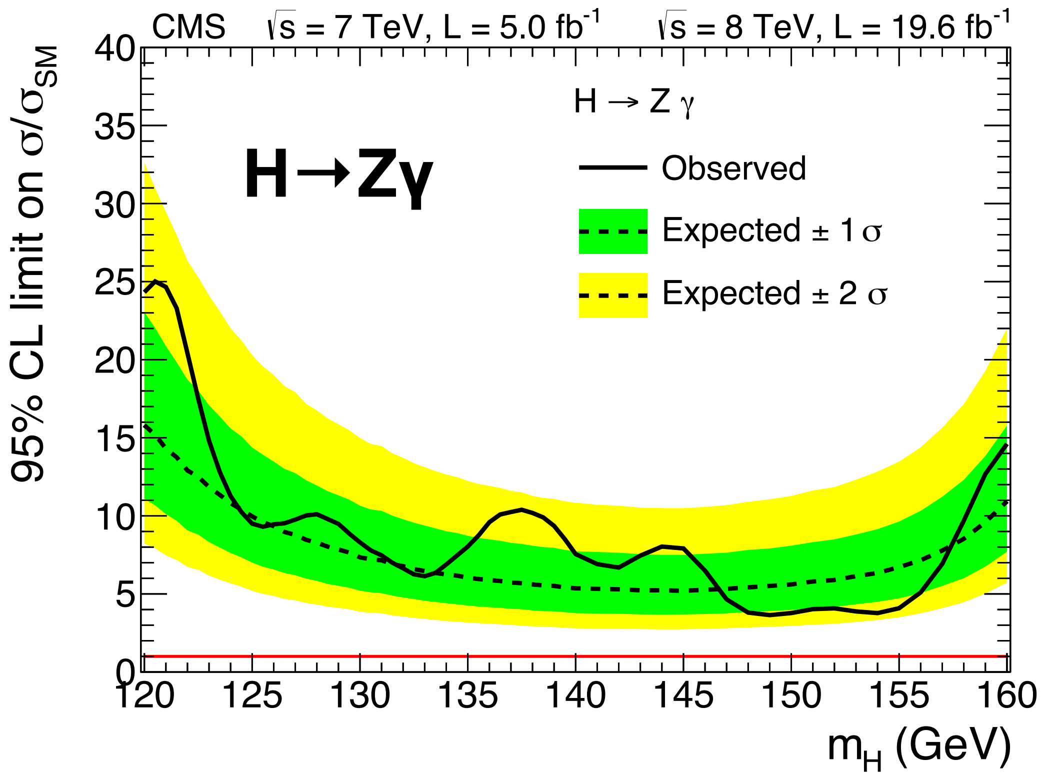
Other channels and properties

H→Zγ

arxiv:1307.5515

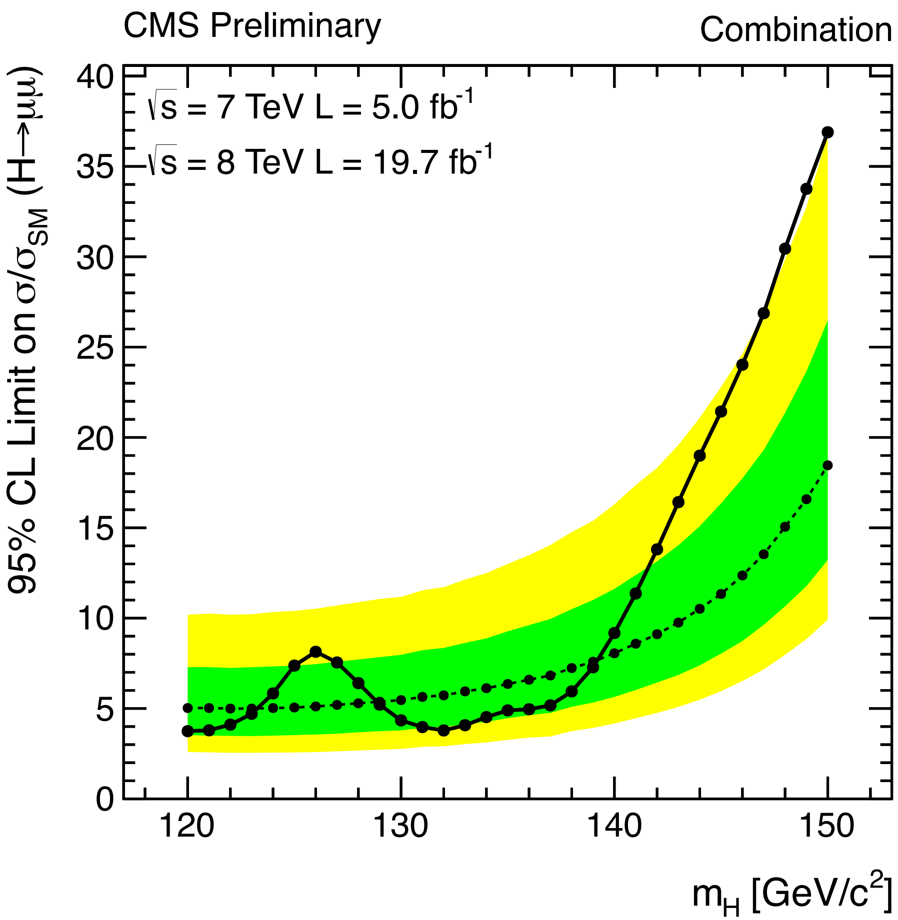


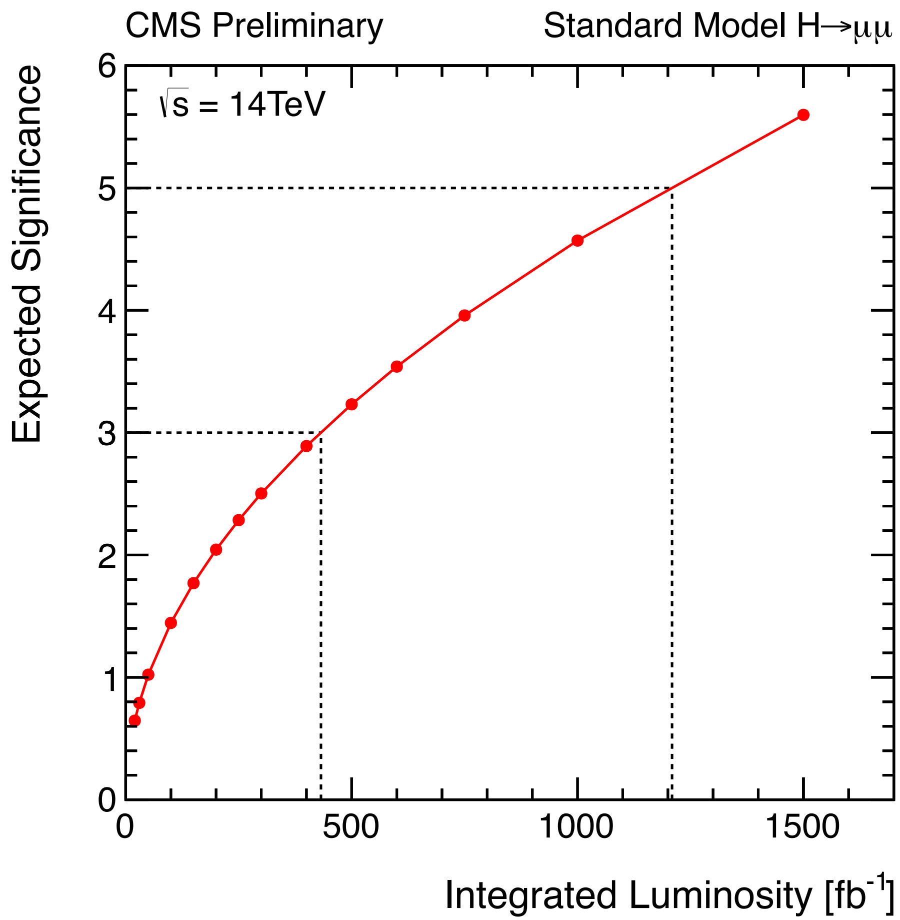
- Interesting because **probes new physics in the loops** (as γγ do)
- ee and μμ channels included
- Categorize in lepton η and photon η and converted/unconverted
- Untagged and VBF categories
- Mass resolution 1-3%
- Getting closer to the SM: at 125 GeV, **exclude ~10x SM**



H→μμ
PAS-HIG-13-007

- **BR(H→μμ) very small** ~2,2.10^{-4} (MSSM and other BSM can predict higher BR)
- **Categories:** 3 Dijet tags, and 2 untagged (low/high Higgs pT) further splitted in inner Barrel, outer Barrel and Endcap
- Resolution 1.6 GeV in best category
- Background estimate from mass fit to data

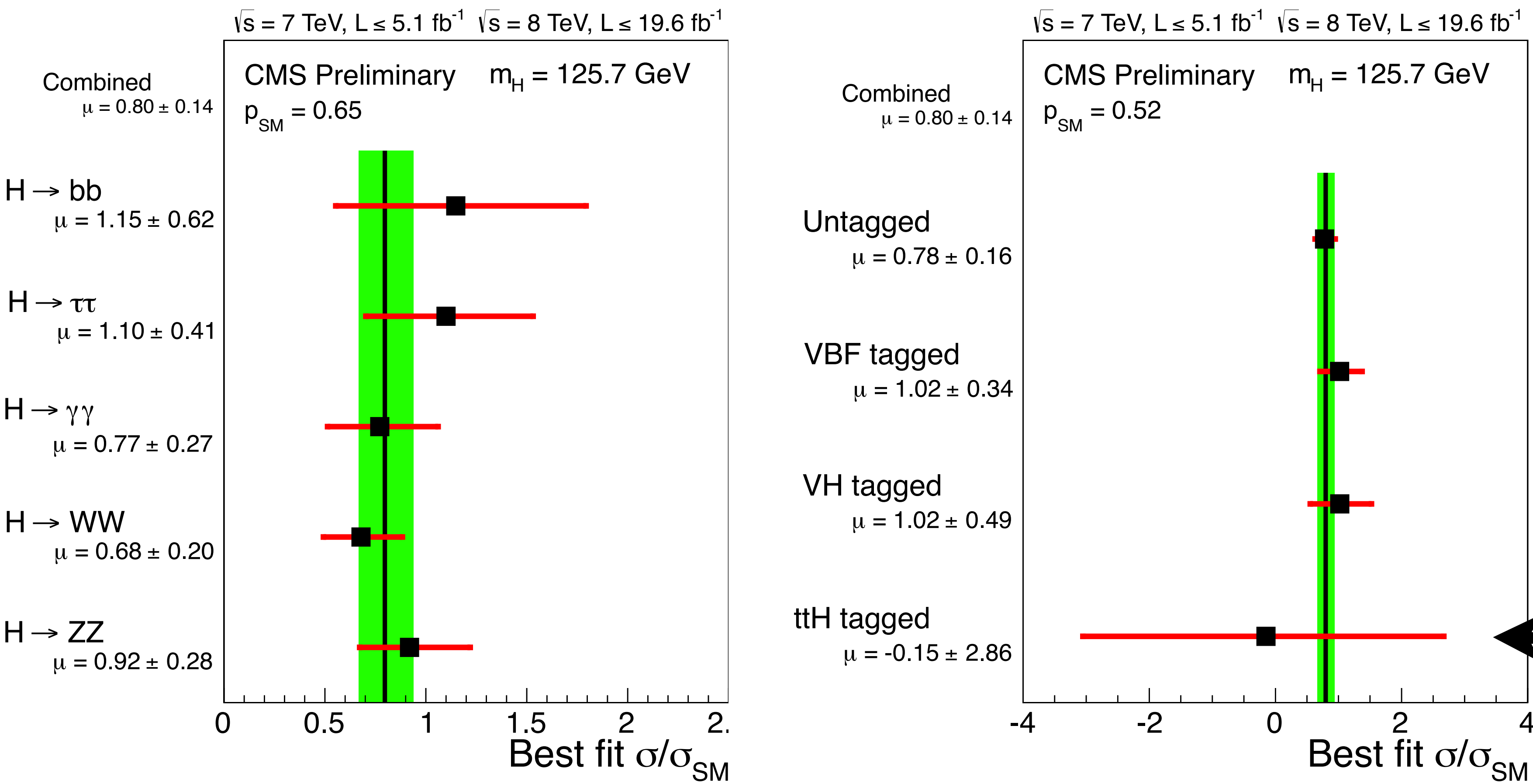




Combination: results

PAS-HIG-13-007

- Entering in precise measurement era
- Combined **best fit μ=0.80±0.14**
- Less known production mechanism ttH, and decay Hbb

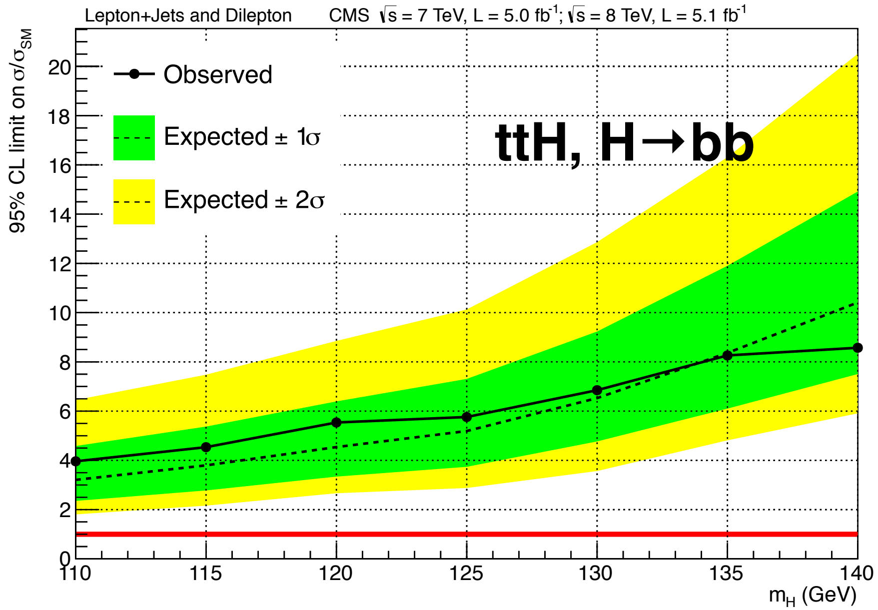


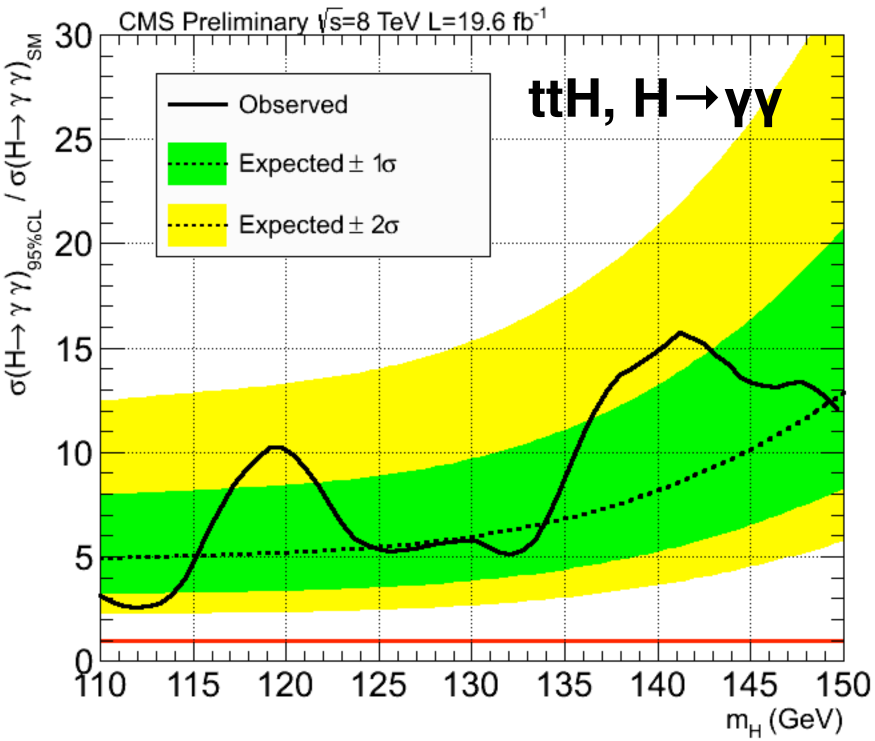
ttH, H→bb only

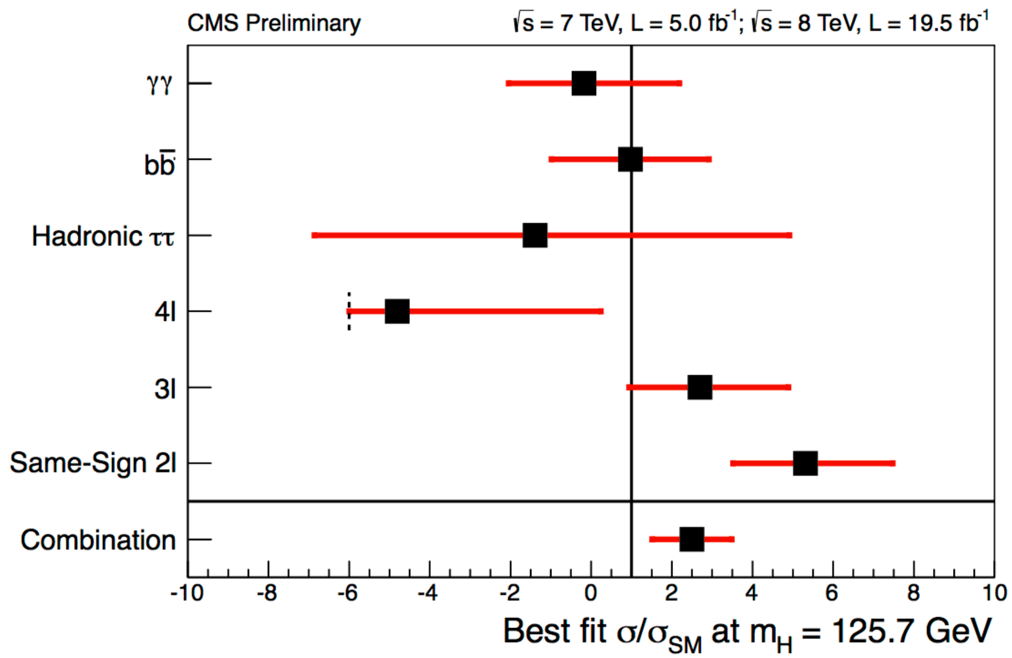
ttH combination

https://twiki.cern.ch/twiki/bin/view/CMSPublic/ttHCombinationTWiki

- **Probing coupling to top quark**
- **Main background: ttbar**
- H→bb,ττ**:** Categorize with number of b-tag and number of jets, use neural network
- Lepton decay: use BDT
- H→γγ: Cut-based analysis
- Combination of all decay channels, measure **μ ~2.5 +/- 1**



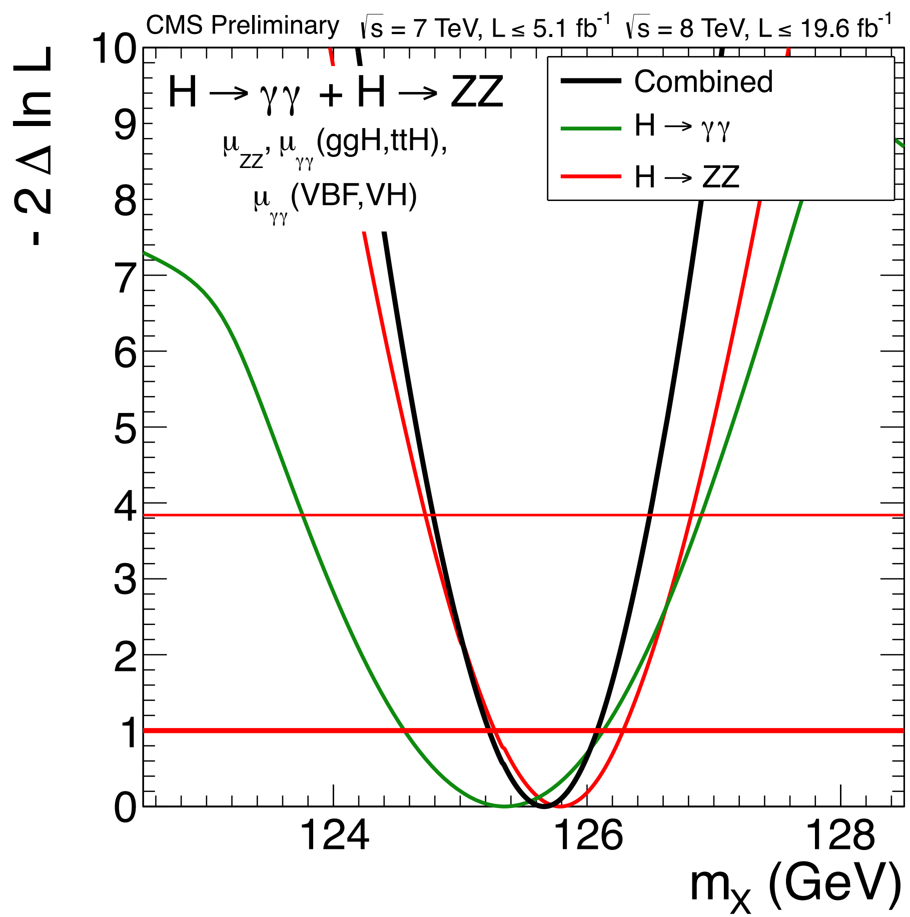


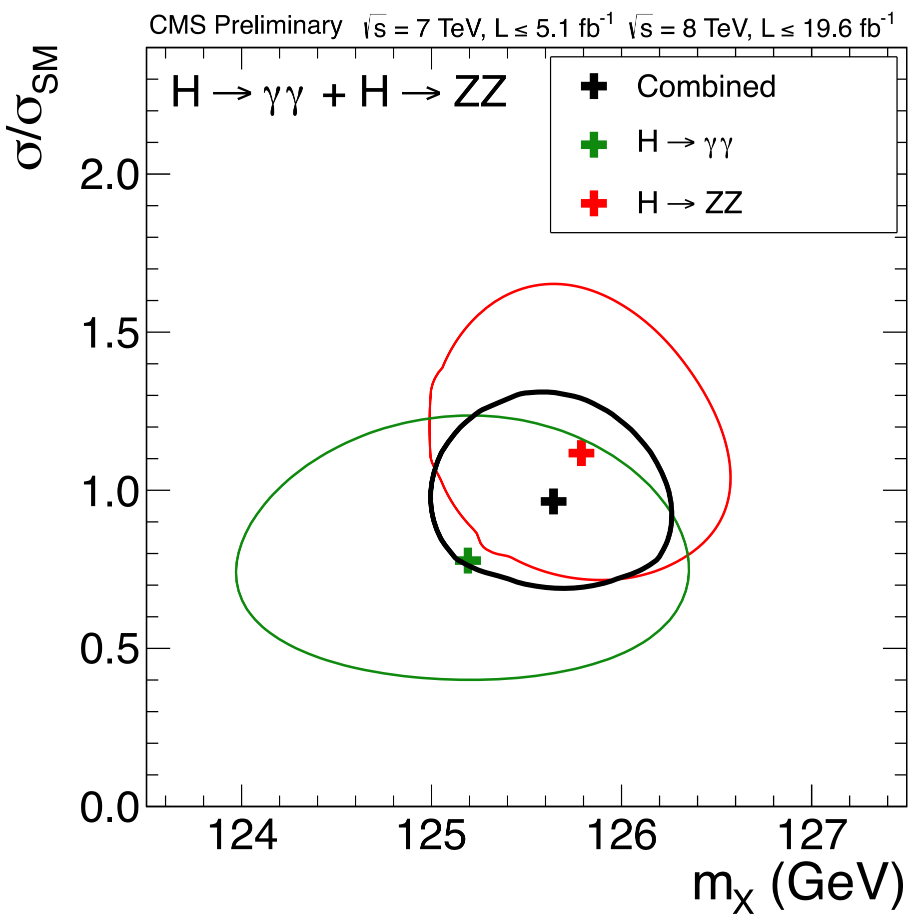


Mass measurement

PAS-HIG-13-007

- Fit from γγ and ZZ: measures **125.7 ± 0.3(stat) ± 0.3(syst) GeV**
- Masses from H→γγ and H→ZZ channels are compatible within 1σ





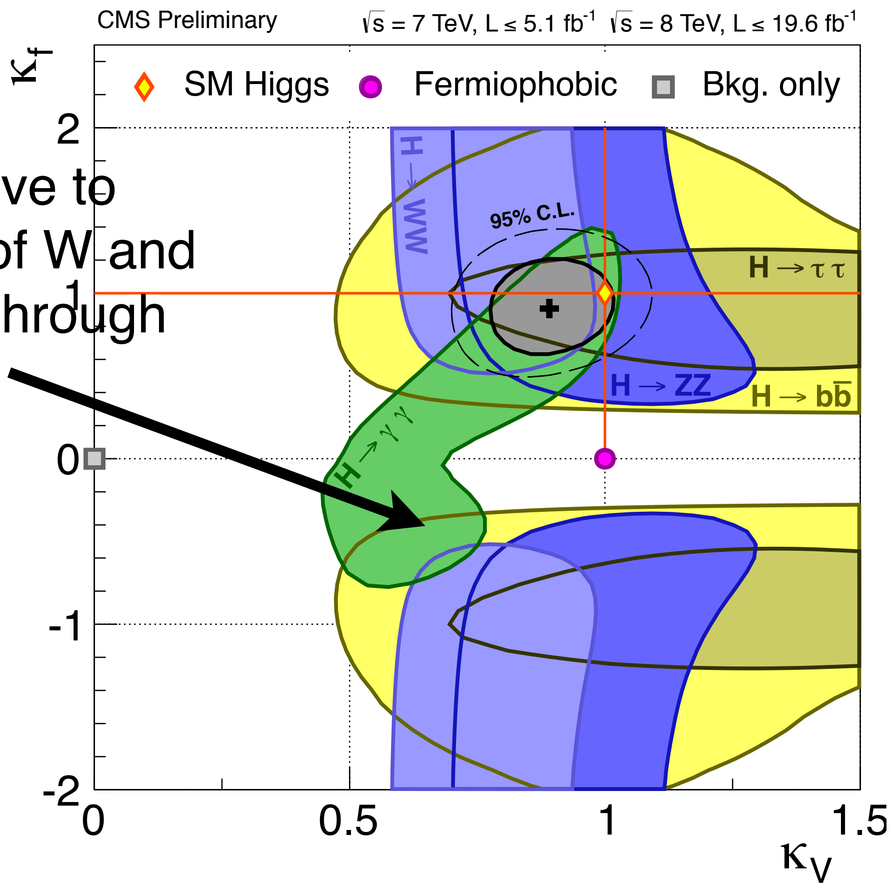
Couplings

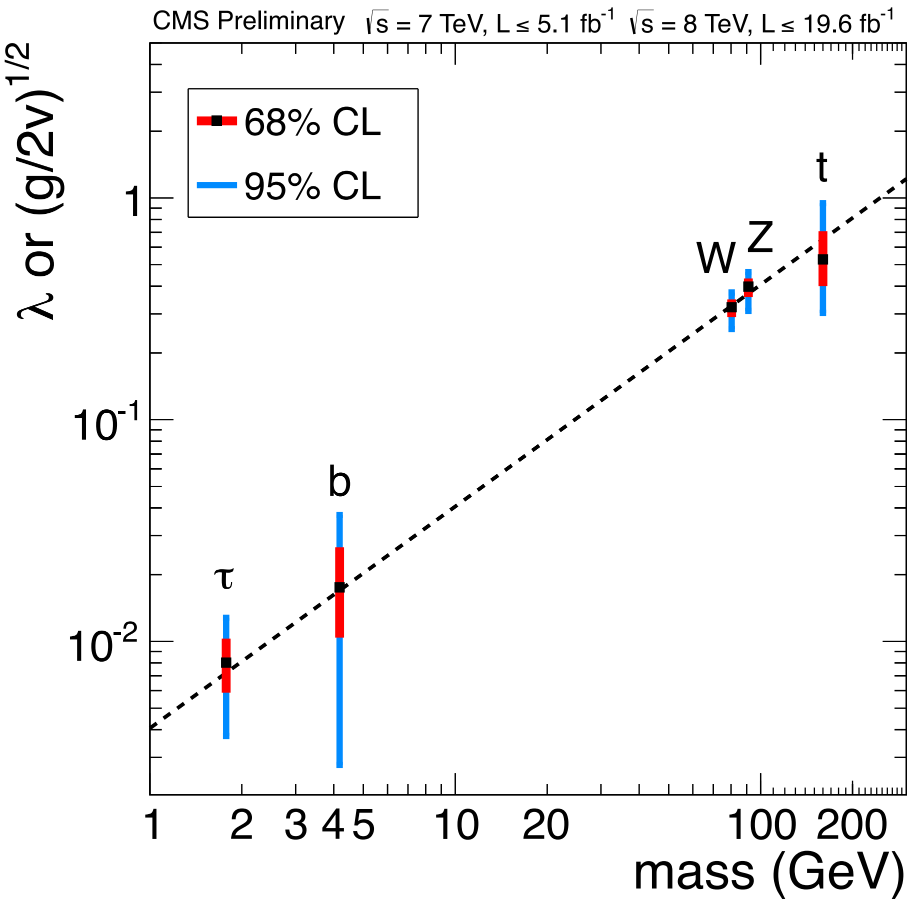
PAS-HIG-13-007

The four main production mechanisms are all related to a **fermion-coupling** (top in gluon fusion loop, ttH) or to **vector boson coupling** (VBF,VH).

Couplings very much compatible with standard model

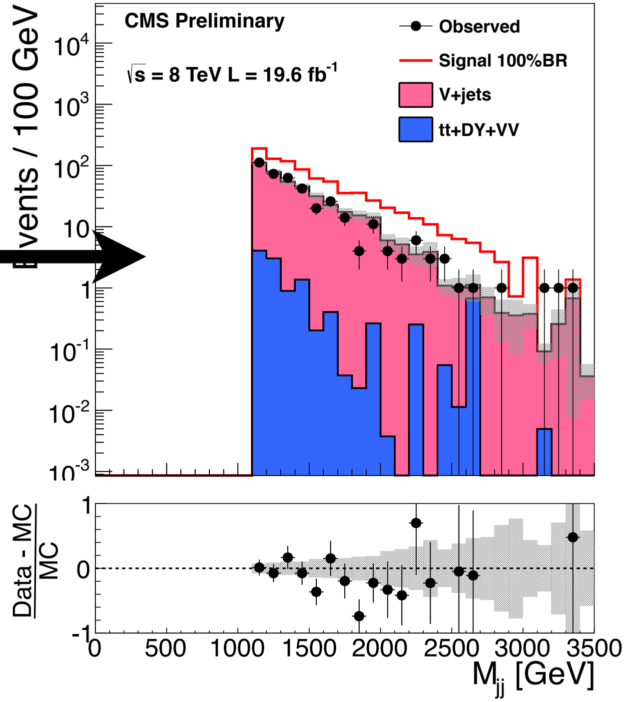
H→γγ sensitive to relative sign of W and top coupling through decay loop

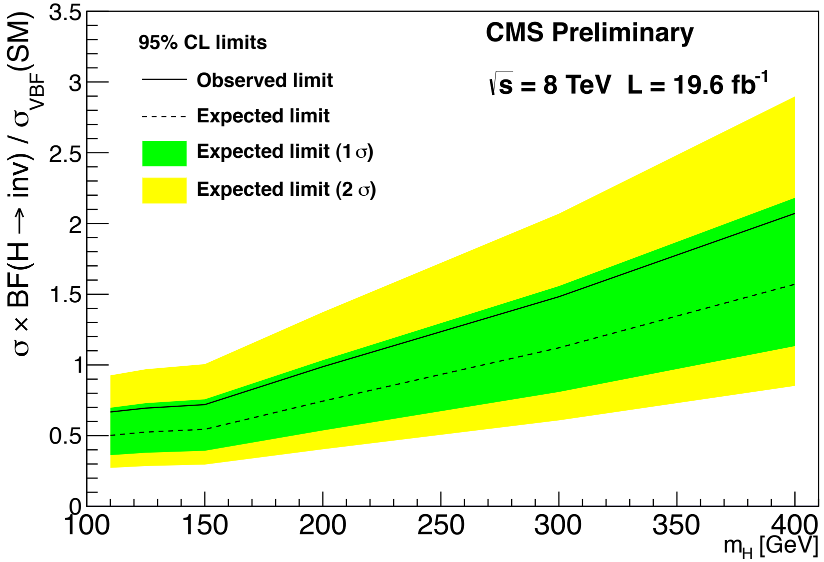




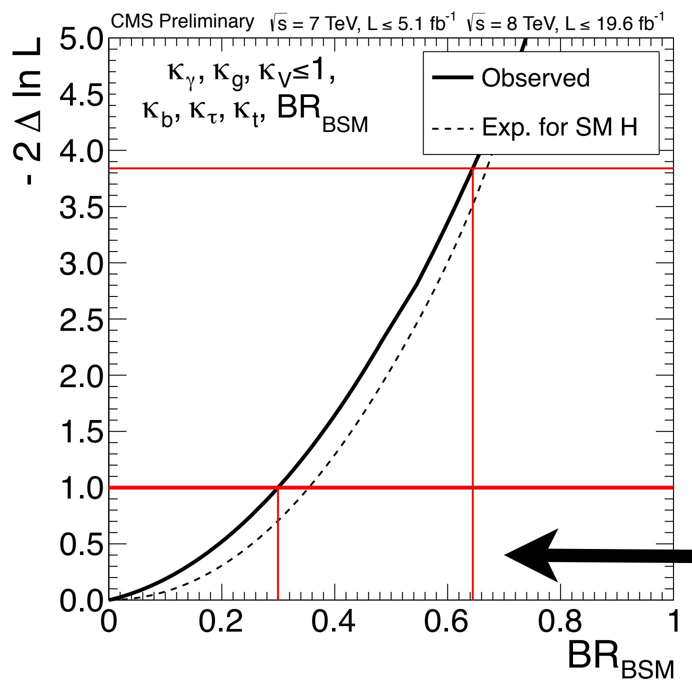
BR(H→invisible)

Direct searches:
VBF H→Invisible
BR(H→Inv)<69%

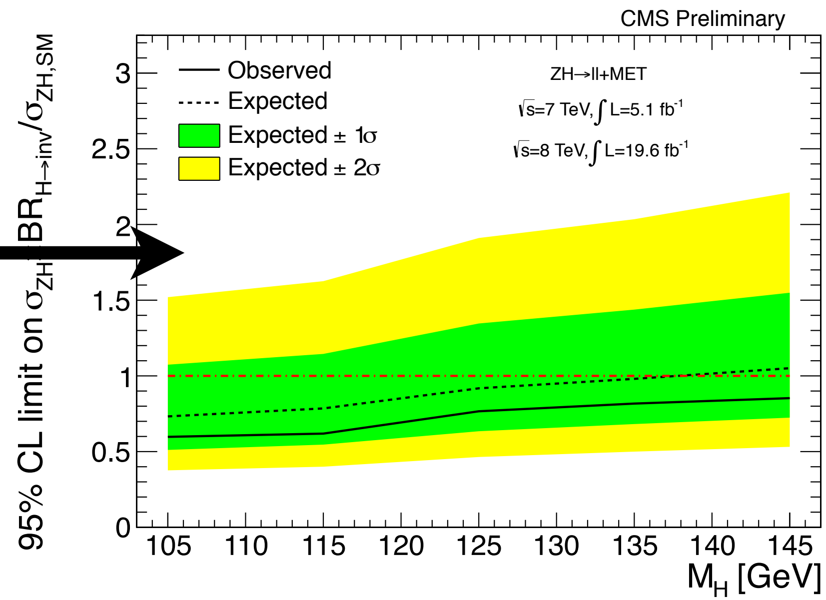




$$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$$



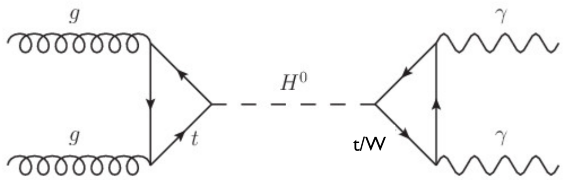
Direct searches:
Z(ll)H→Invisible
BR(H→Inv)<75%

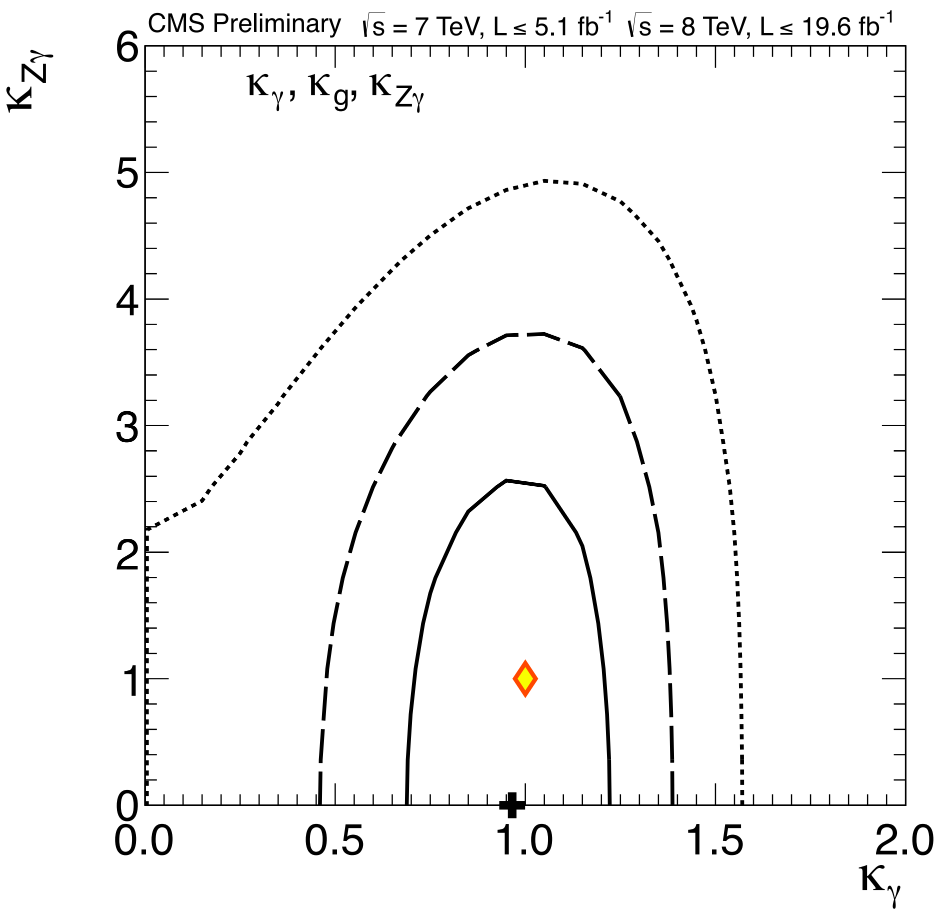


Induced from couplings:
BR(H→Inv)<64%

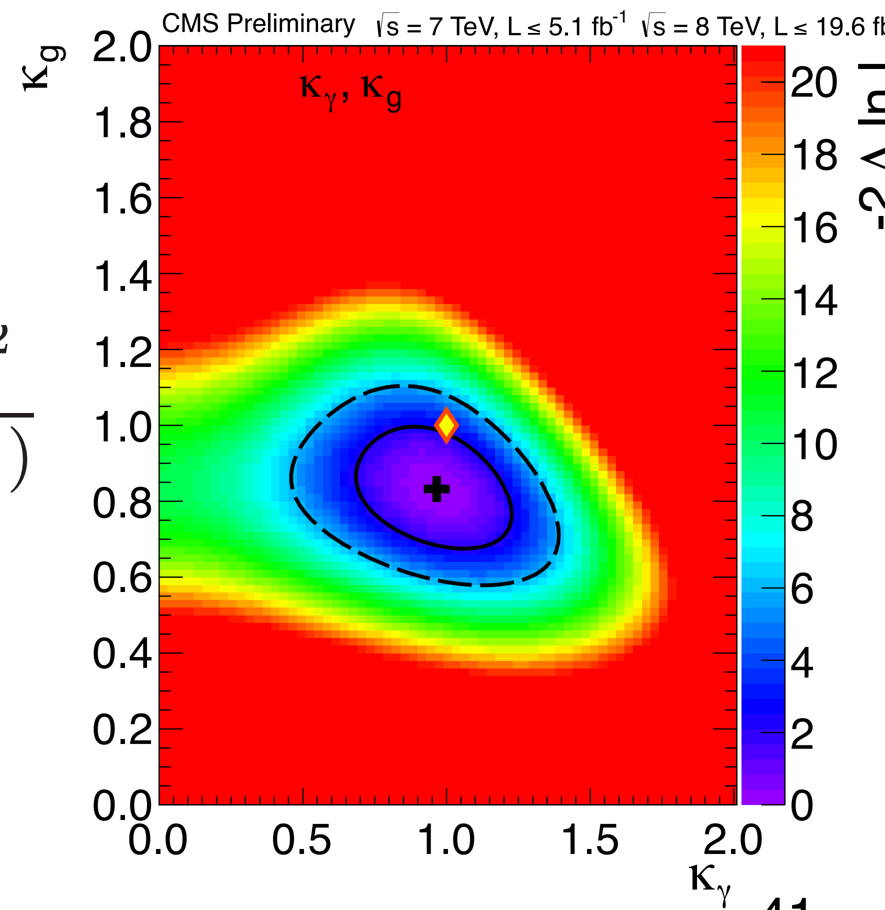
New physics in loops

New heavy particles running in **gg→H→γγ in gg→H→Zγ loops** could enhance / decrease the rate: change **couplings to gluon and to photons**

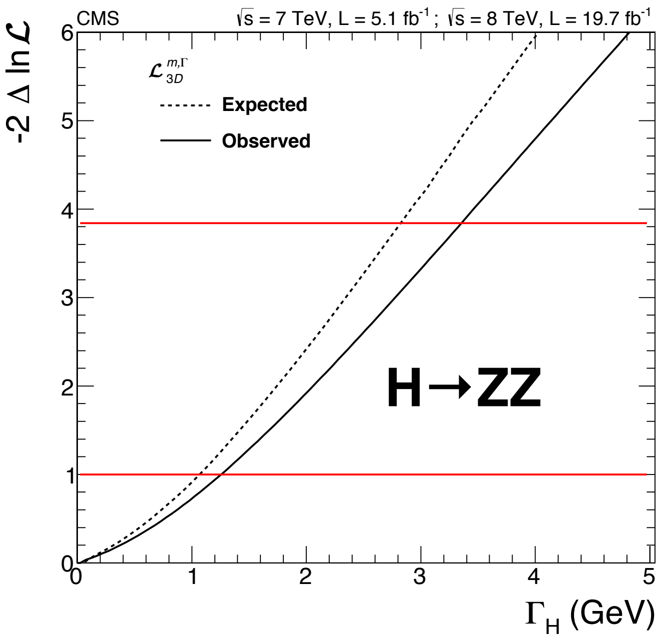




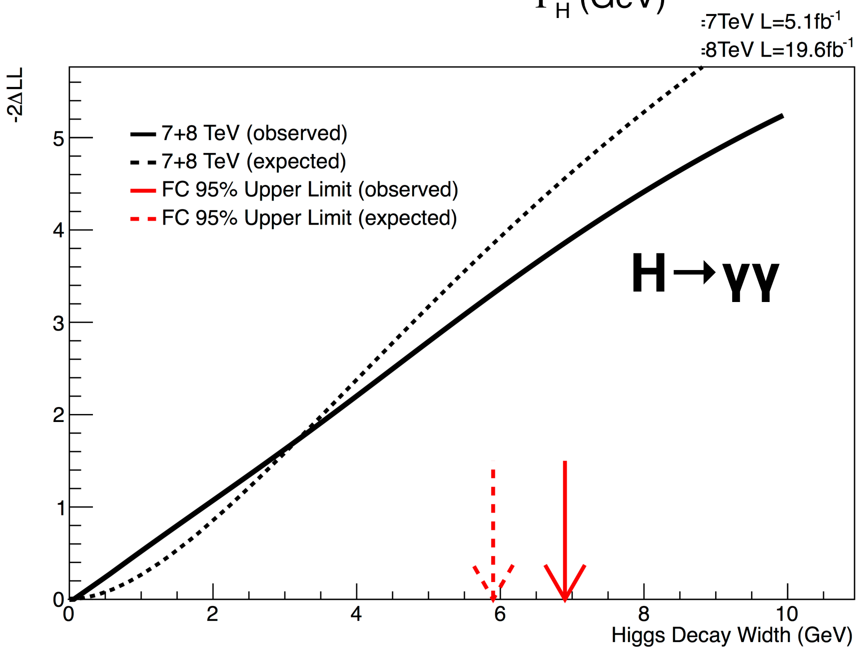
$$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$$



Higgs total width



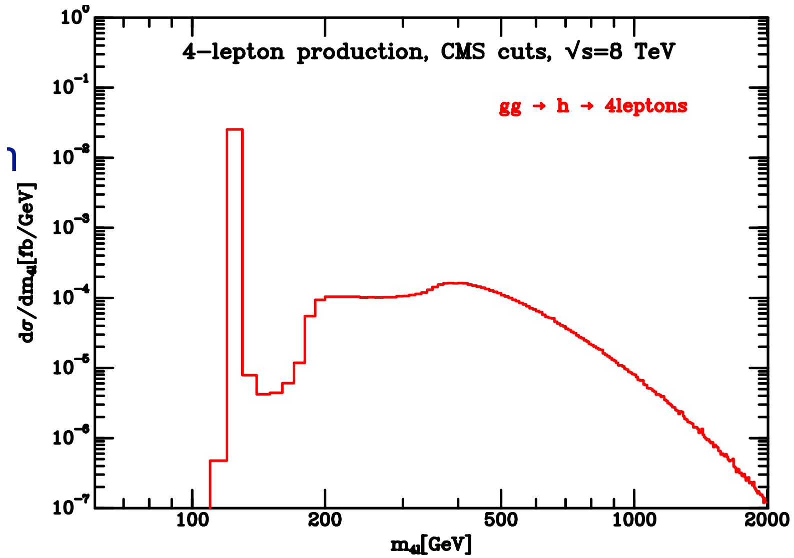
Higgs total width measurement is limited with detector resolution

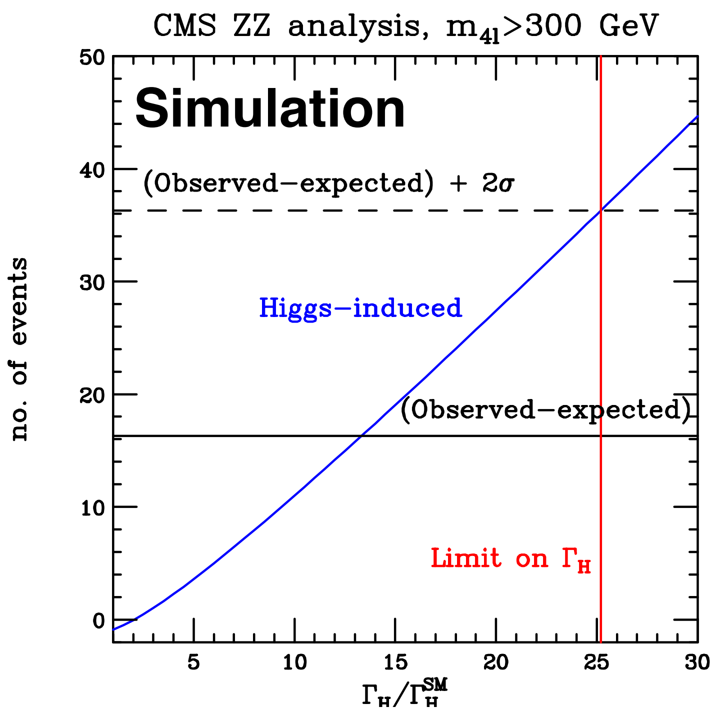


Solution: interferometry

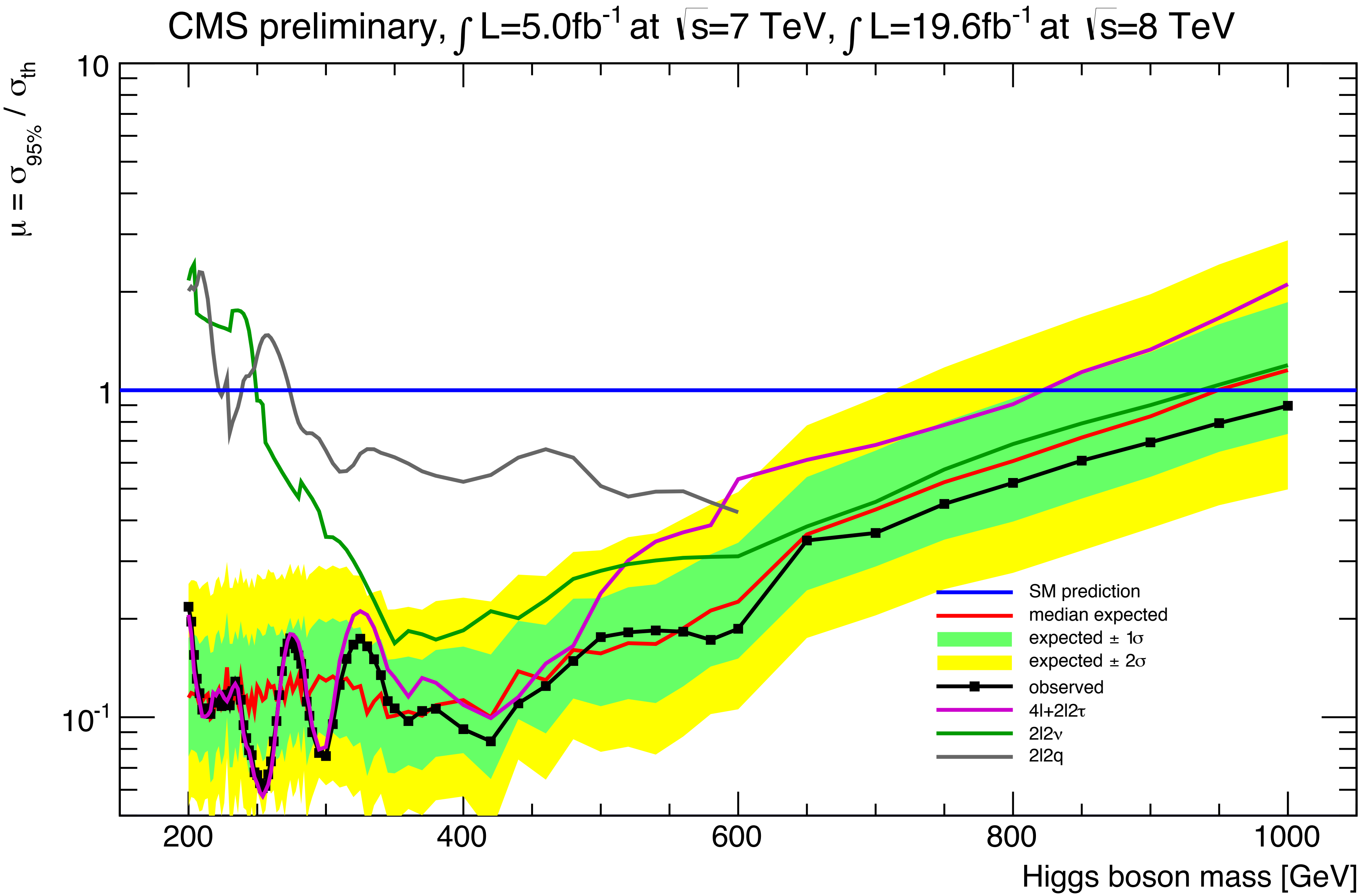
- Use tail of mass peak

(see for instance arxiv:1311.3589)





High mass searches with H→ZZ

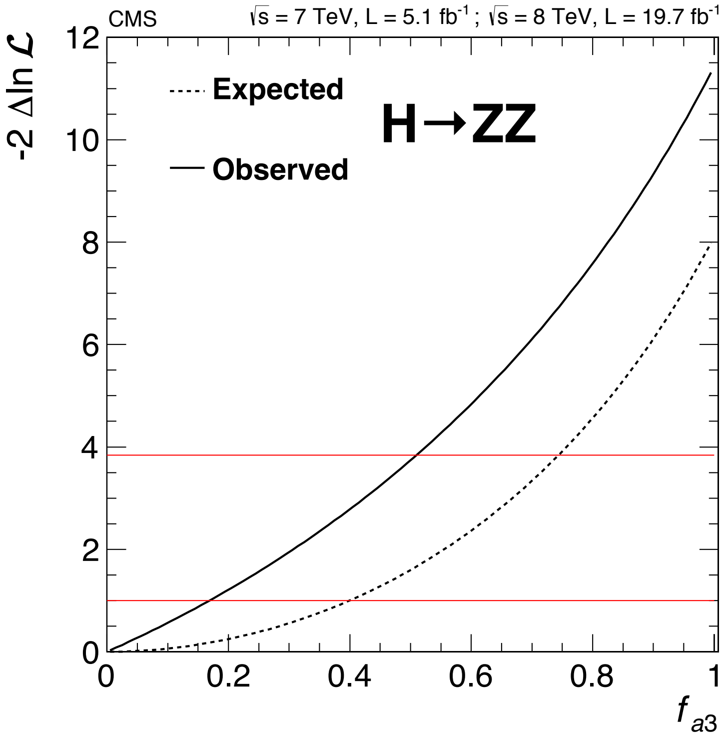


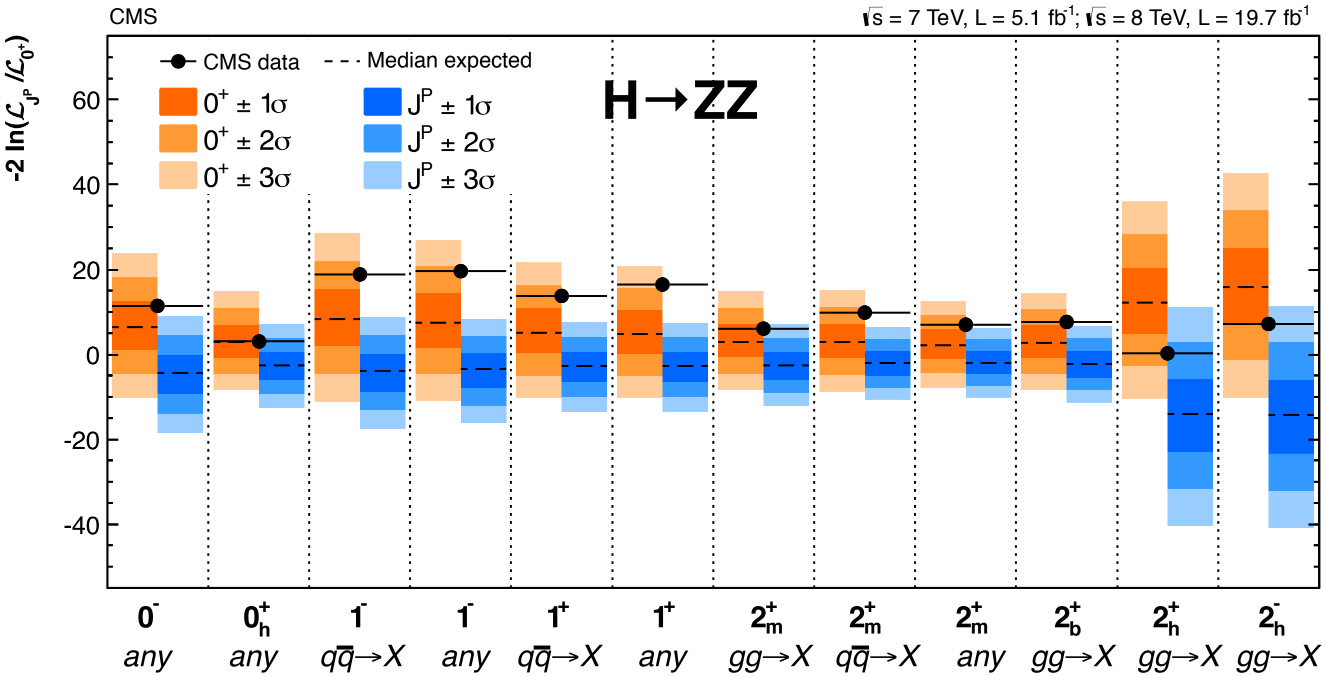
Spin/Parity measurement

- Cannot measure directly spin (too much parameters in the lagrangian, not enough statistics) => Need to **test some reasonable benchmark models**
- Testing **mixture of 0^- and 0^+** hypothesis (fa3 param.) using ZZ kinematic discriminant
- Testing minimal graviton couplings **2^+** and higher dimension tensor structure
- Testing production mechanisms via gluon fusion and qqbar

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

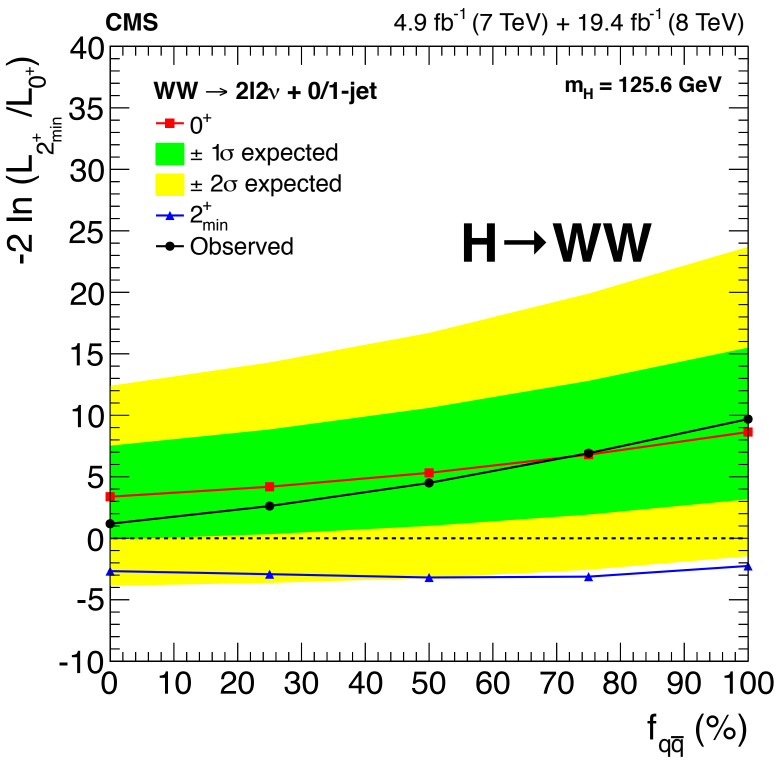
fa3 = A3/(A1+A2+A3)

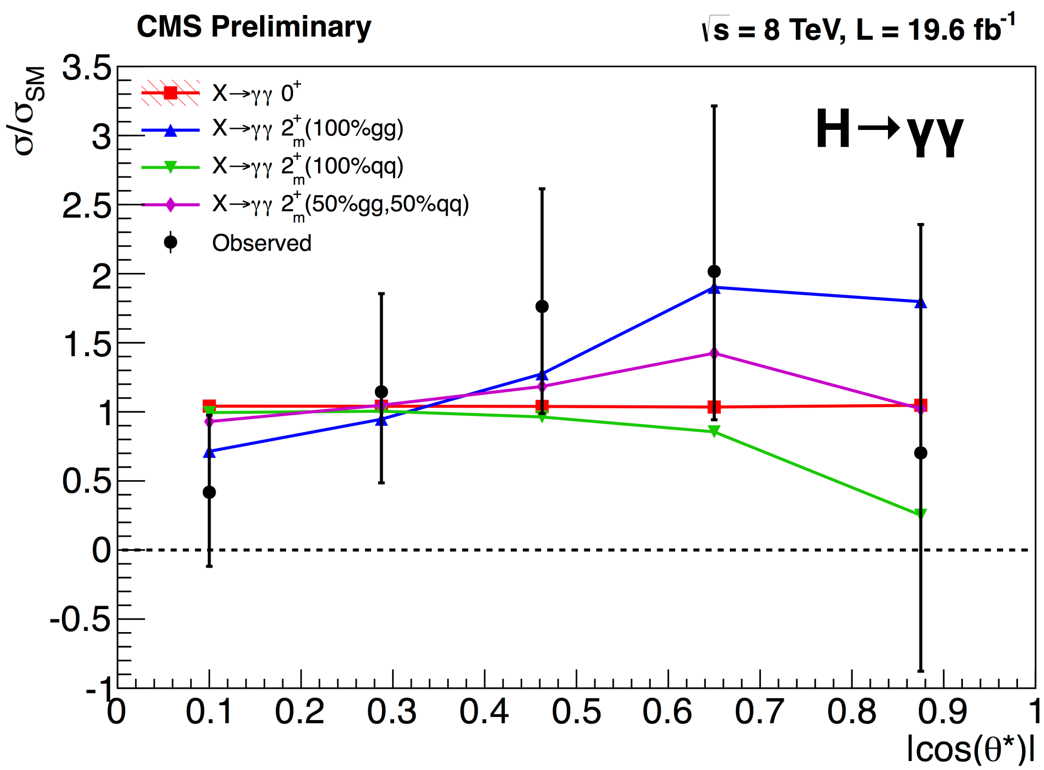




Spin/Parity measurement

- Overall data from H→ZZ and H→WW points to an agreement with standard model
- H→γγ needs more data
- Will need more data to exclude more complicated tensor structures





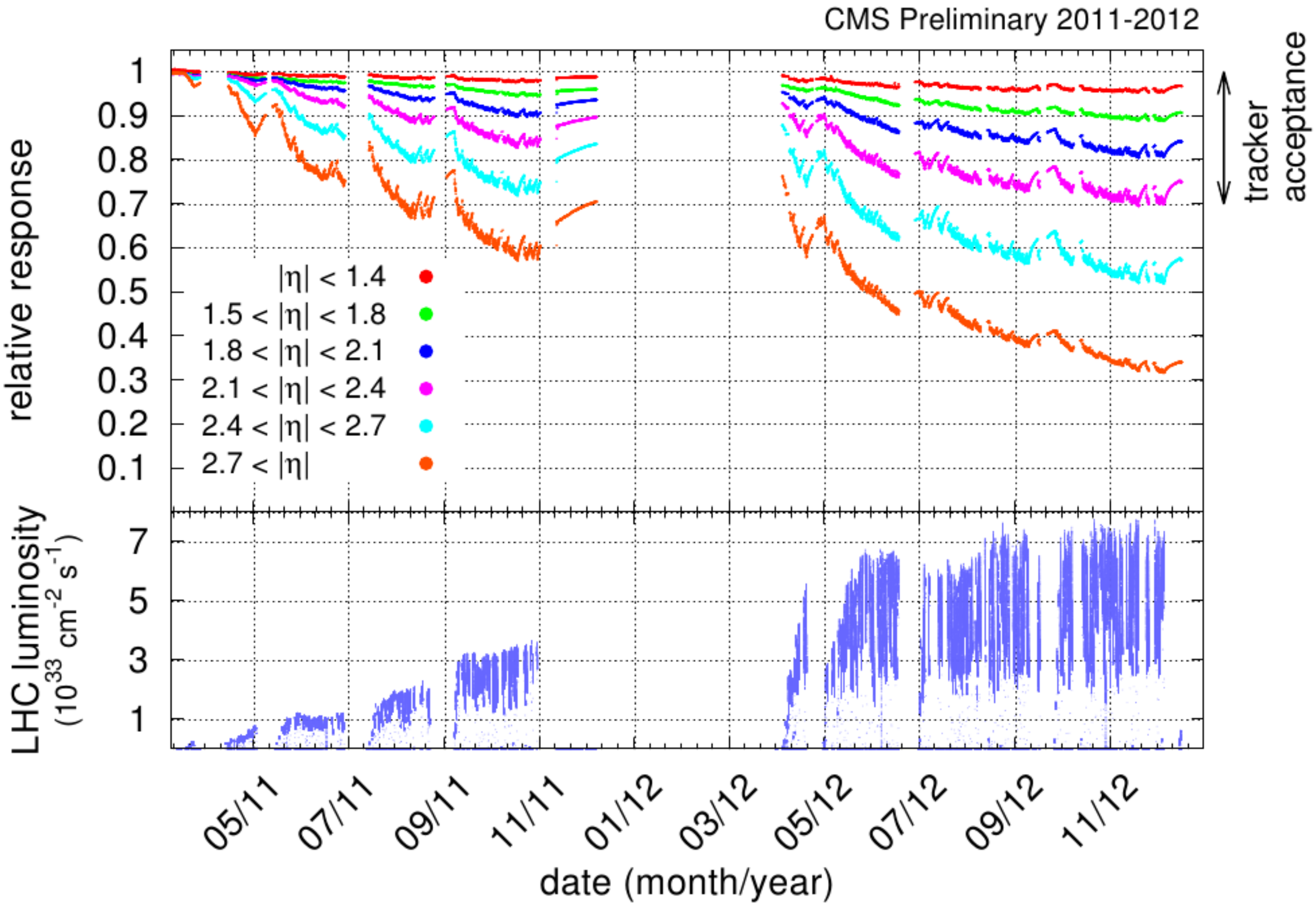
Conclusions

Higgs searches at CMS

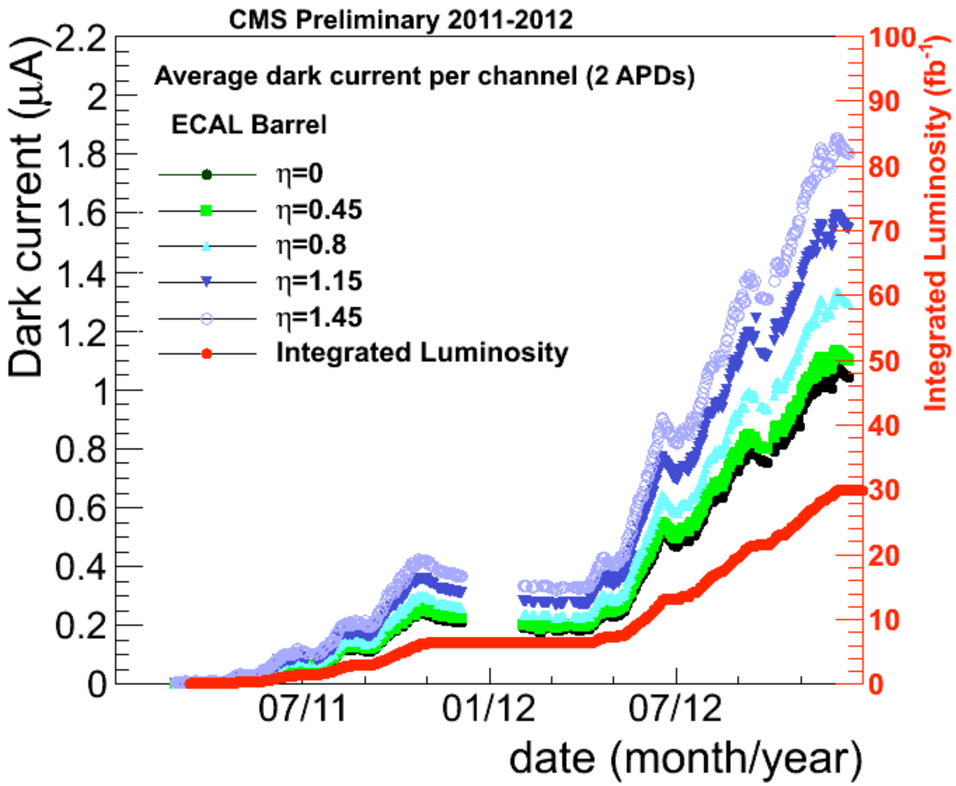
- **New particle existence** is now well established
- **Couplings** seems very much **compatible with SM**, although coupling to top and bottom needs more data (decay to bottom quarks still needs evidence)
- **Mass: 125.7 ± 0.3(stat) ± 0.3(syst) GeV** (to be updated for legacy paper)
- **Spin measurement compatible with SM** so far
- **LHC Run II** will allow to probe further spin and couplings, access to small BR final states, search for additional Higgses... and hopefully find some new physics beyond standard model!

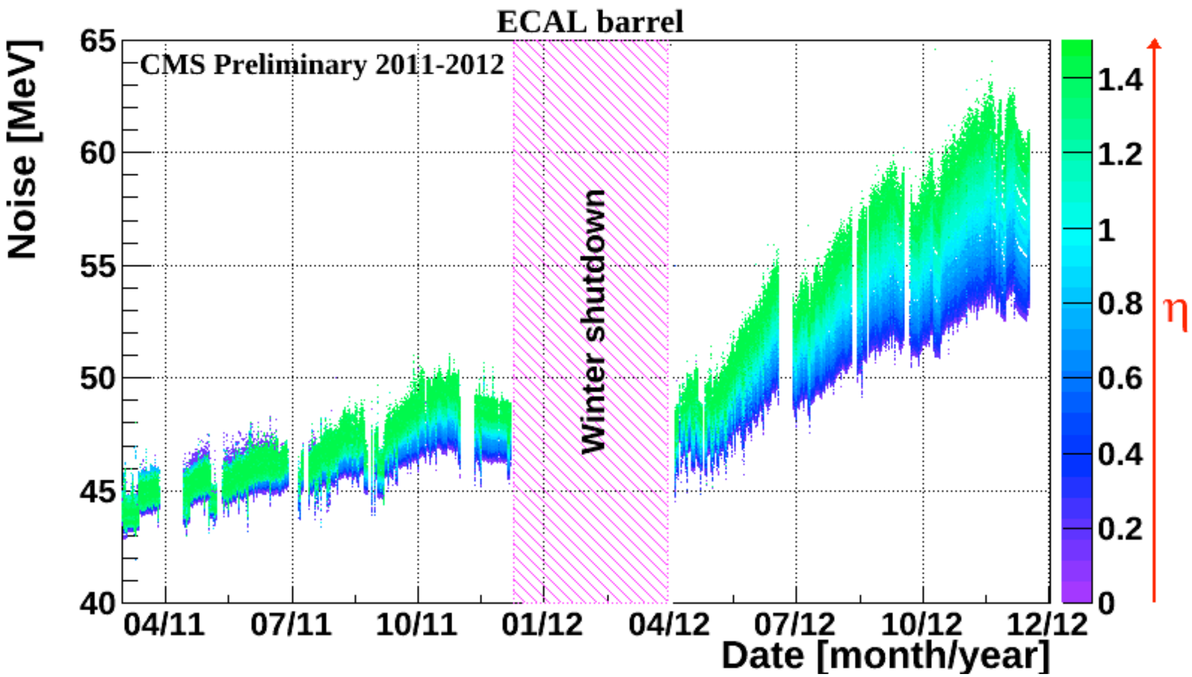
BACK-UP SLIDES

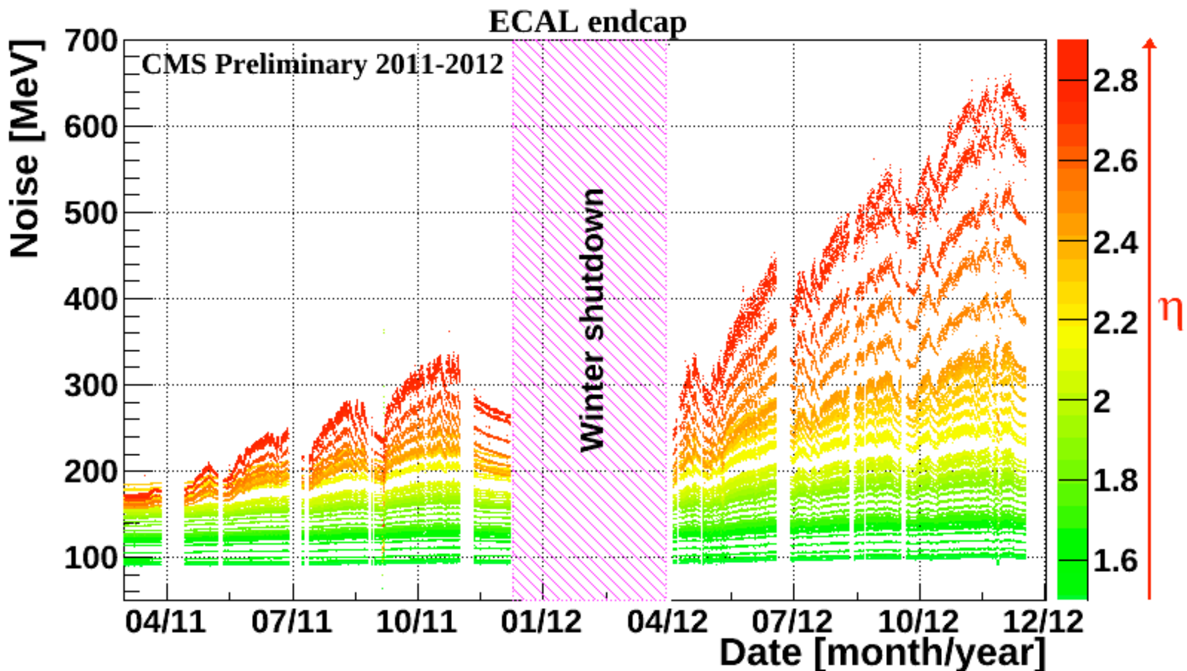
Laser monitoring



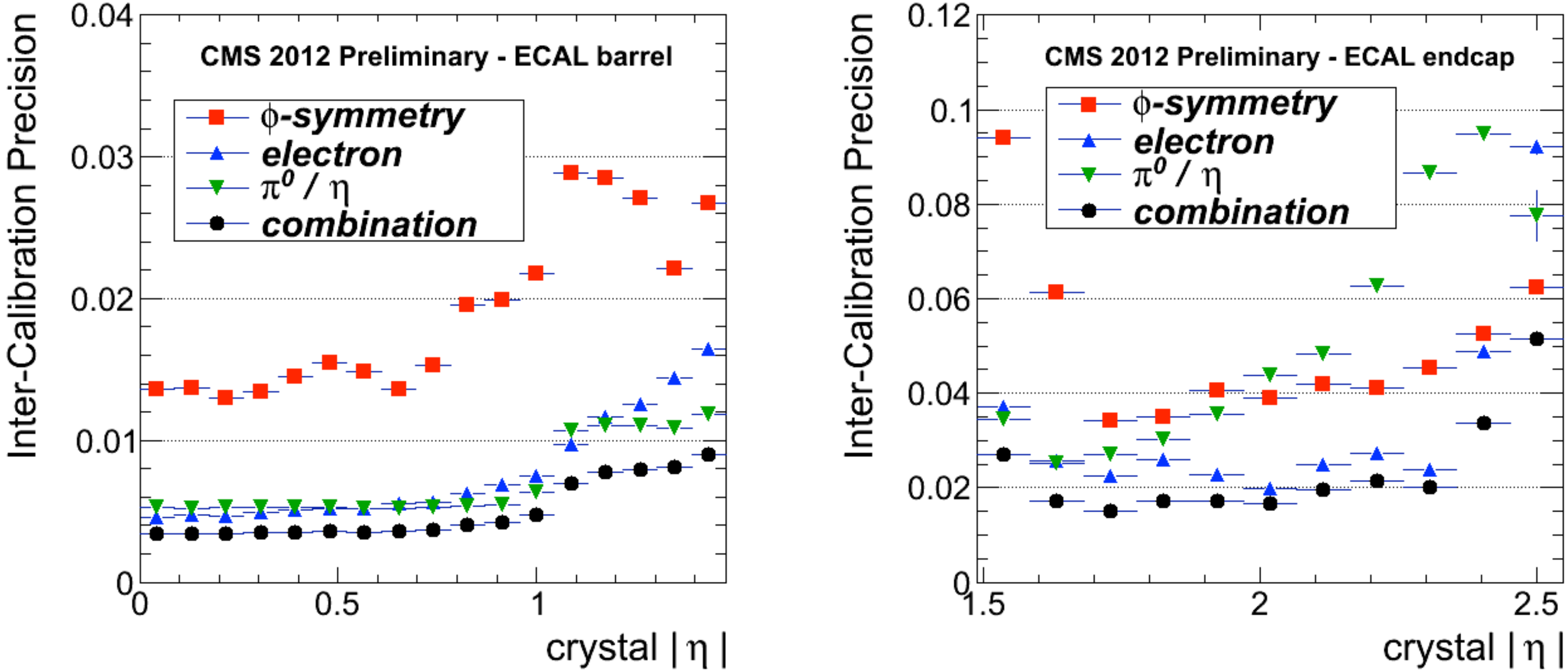
Noise in APD/VPT



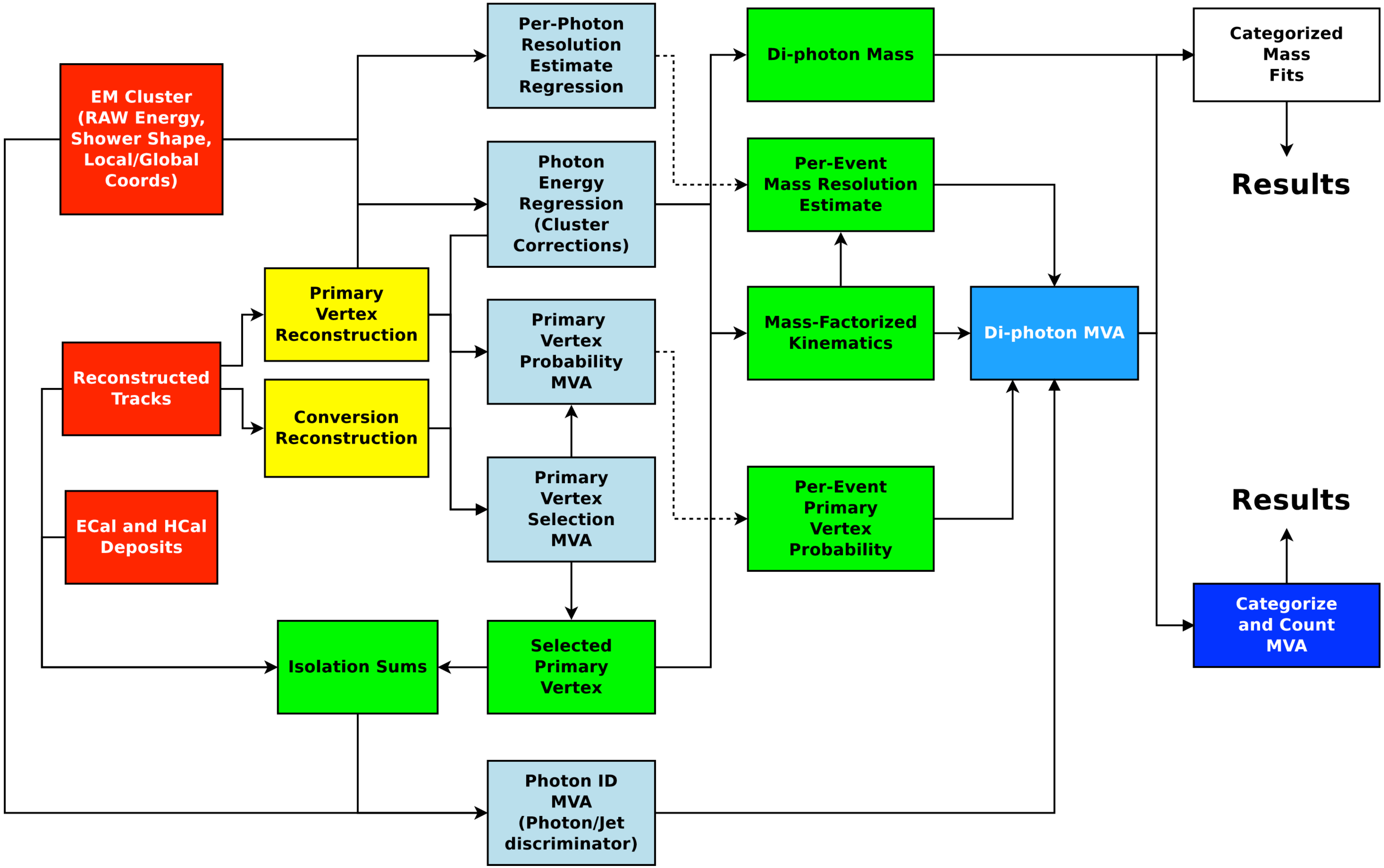




Intercalibration precision



H→γγ flowchart

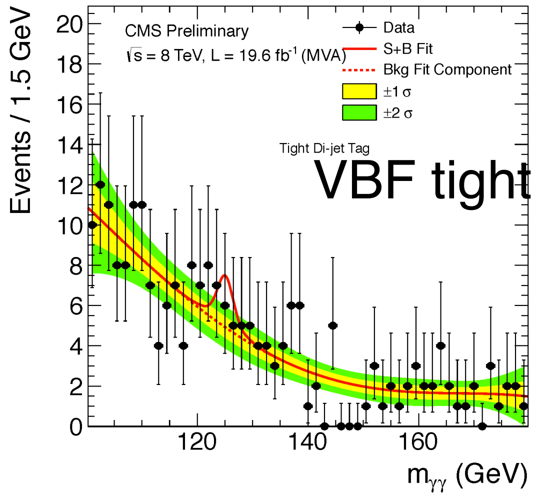


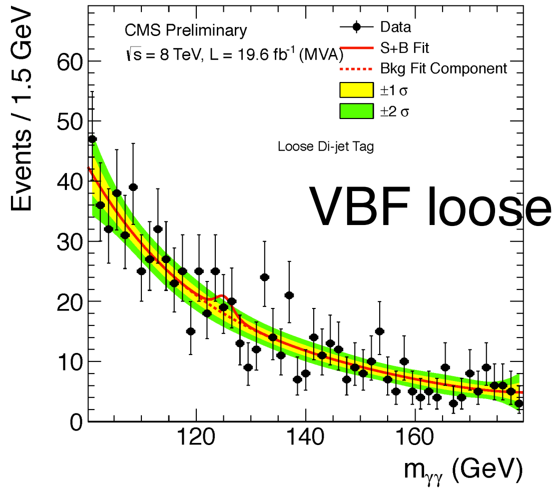
Exclusive channels: VBF and VH

Sensitivity to production mechanisms and Higgs-Vector boson coupling

VBF tags:

- VBF is higher γγ p_T, two forward jets
- **Dijet BDT** using diphoton/jets kinematics
- Define two categories: s/b~0.5 and s/b~0.2

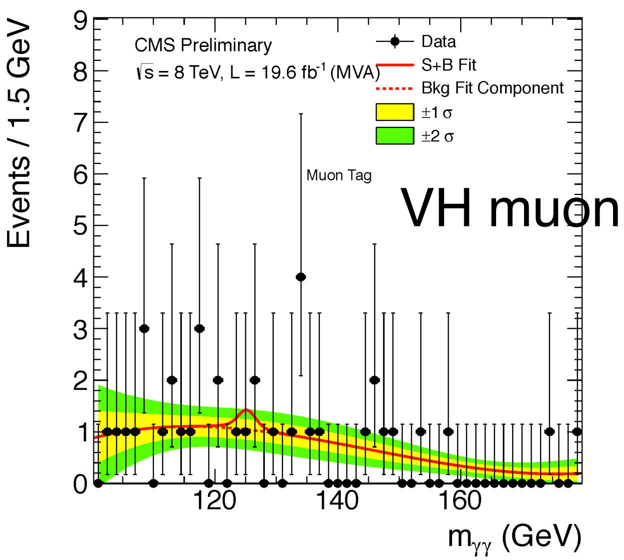


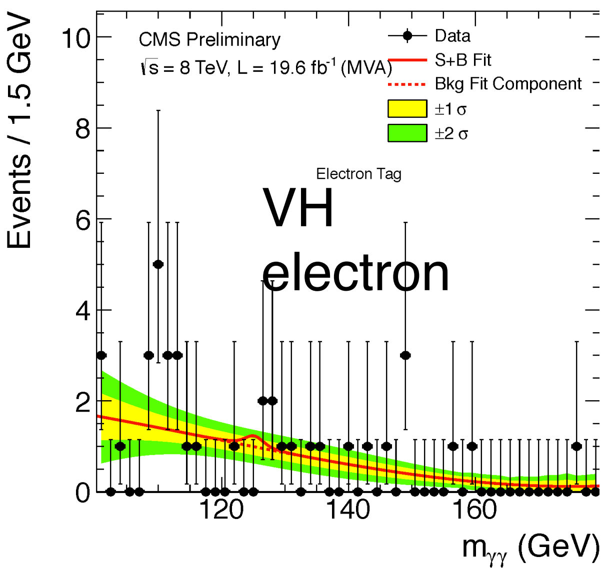


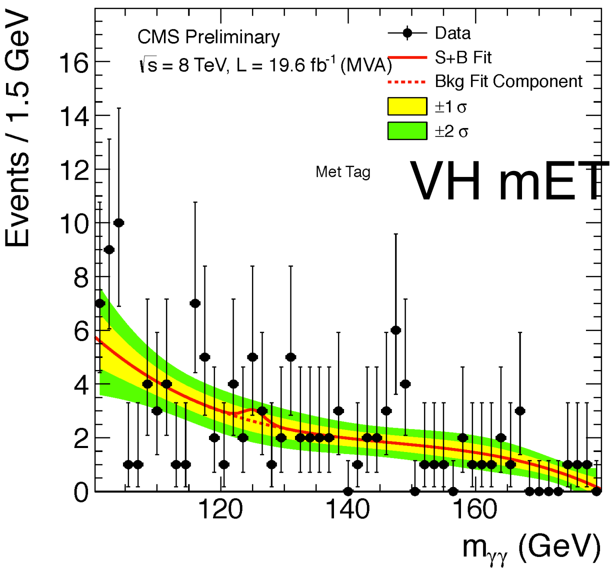
Gluon-gluon fusion contamination in VBF categories ~20-50%

VH tags (WH, ZH production):

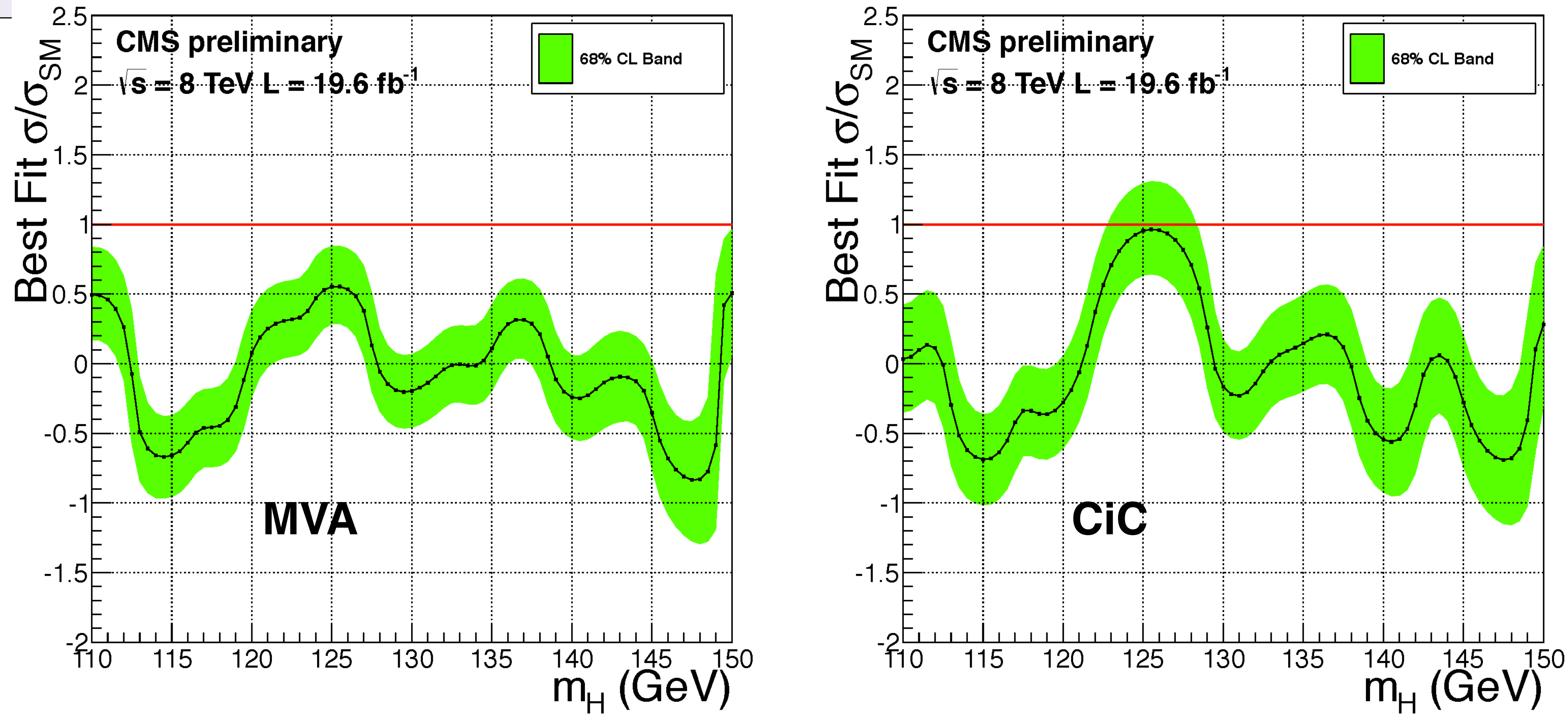
- Two lepton categories, **muon or electron**
- One **mET** category





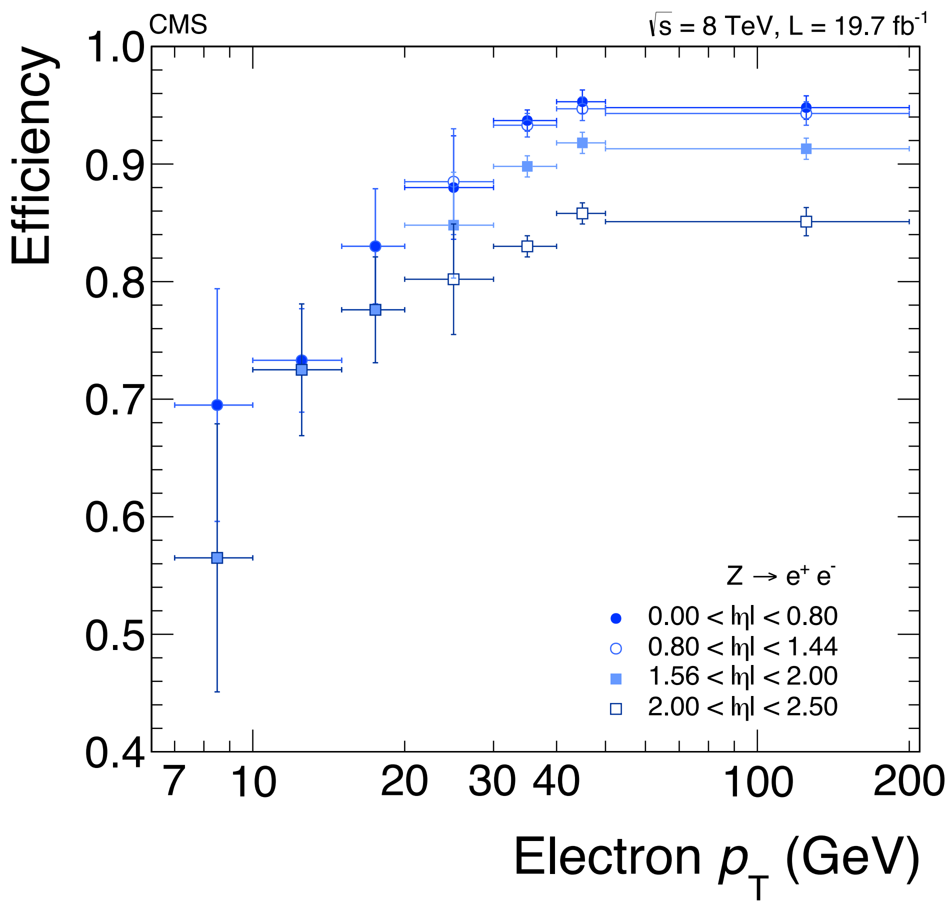


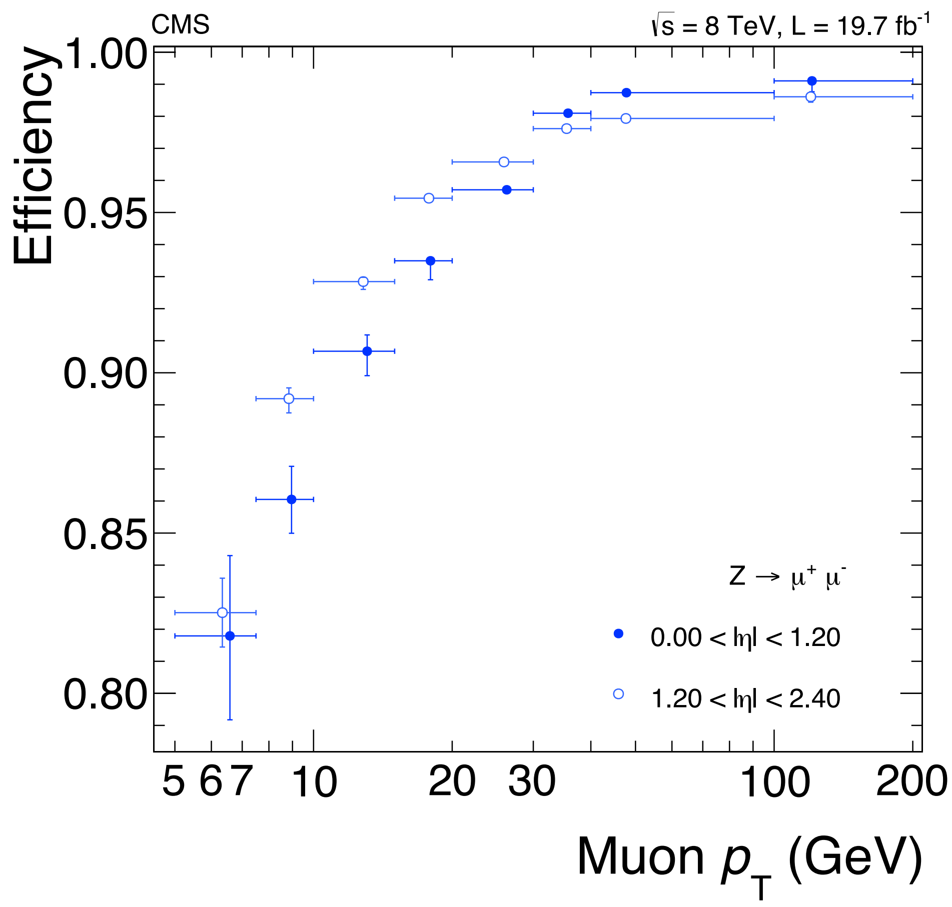
H→γγ 8 TeV only



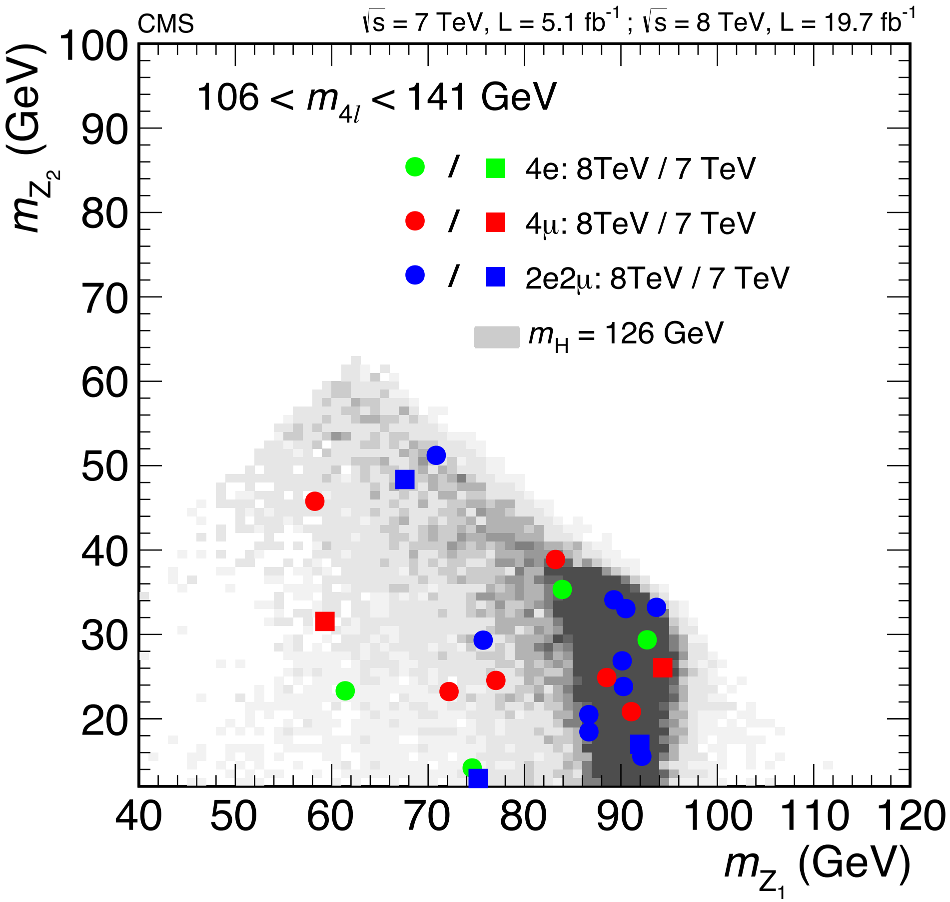
	MVA analysis (at m_{H}=125 GeV)	cut-based analysis (at m_{H}=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

H→ZZ: lepton efficiency

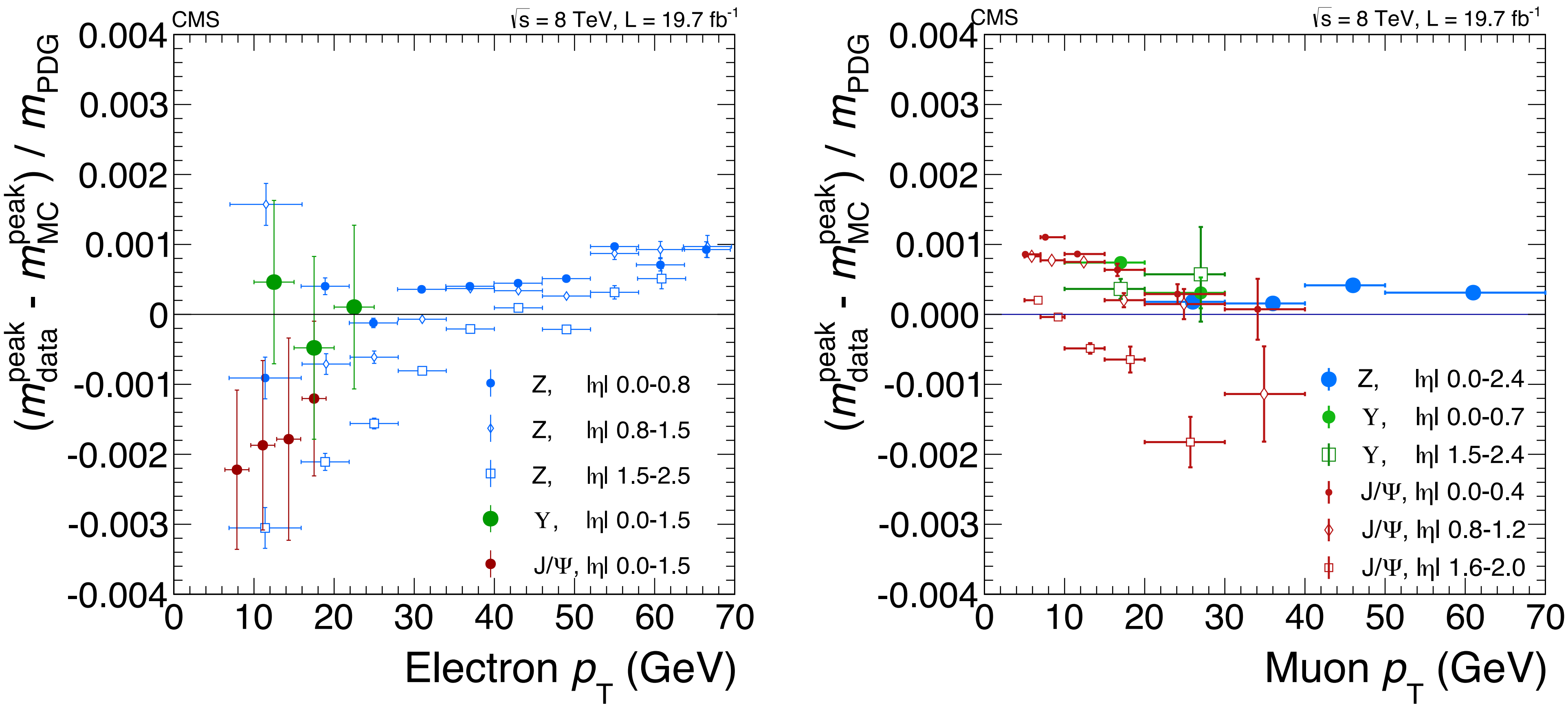




H→ZZ: Z1 and Z2 masses



H→ZZ: mass scale

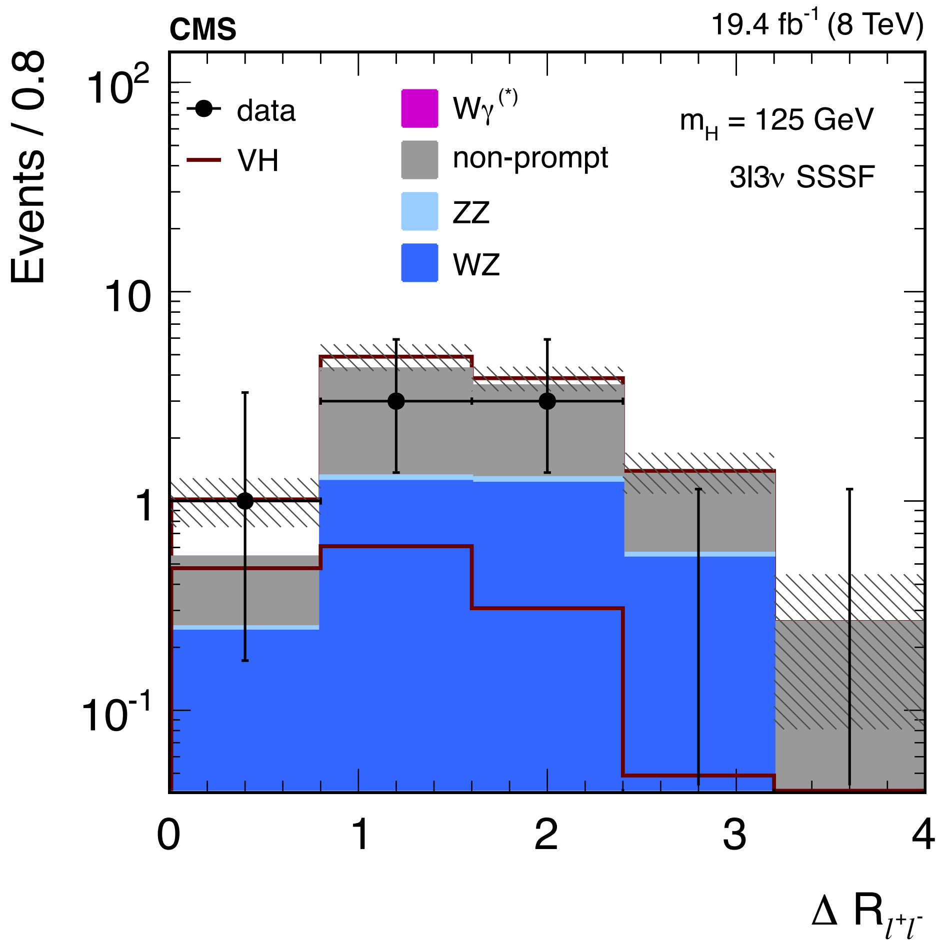


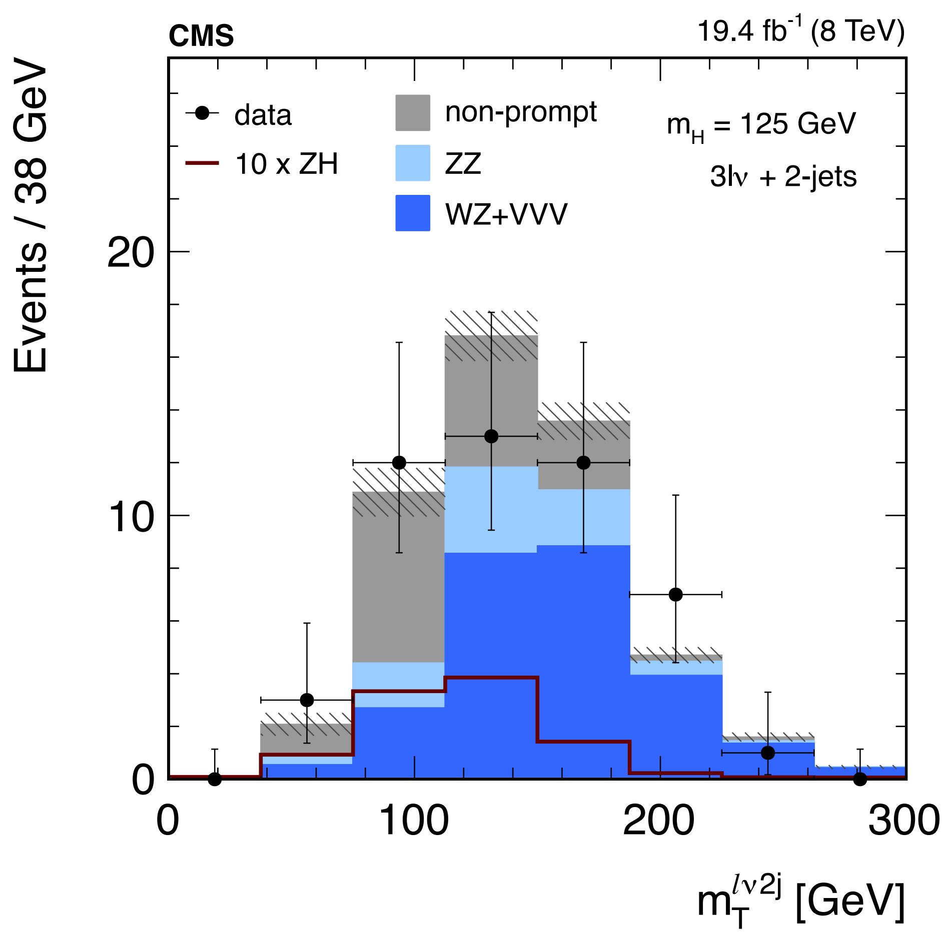
H→W+W- analysis

arxiv:1312.1129

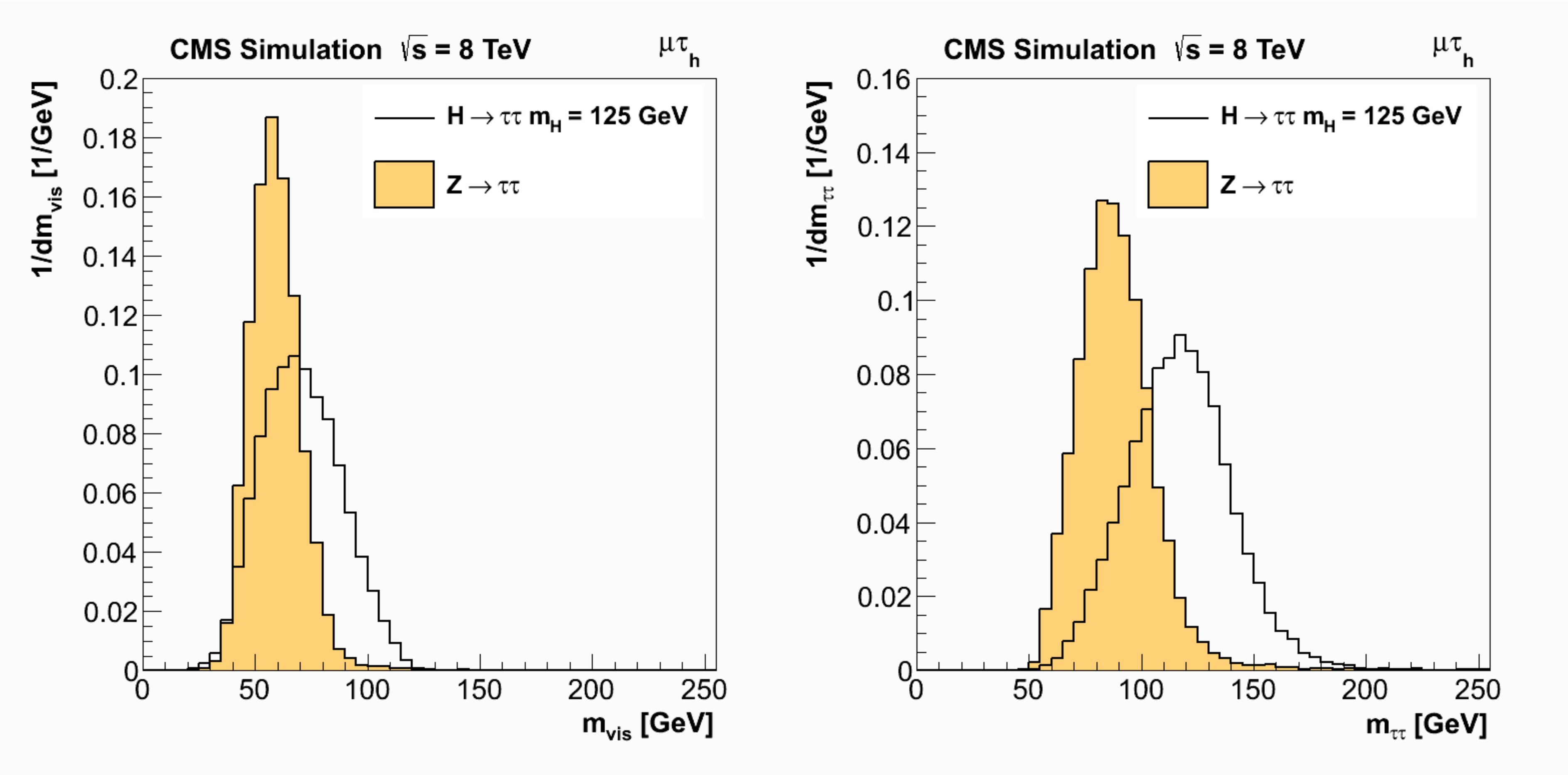
Trilepton final state also used: WH→3l3ν, ZH→3lν+2jets

- Main background: WZ, non-prompt leptons (Z+jets, top)
- Shape analysis





$H \to \tau^+\tau^-$ mass



Coupling measurement

Model: EFT with the chiral lagrangian in the EW sector

- Grojean et al. [arXiv:1207.1717], Azatov et al. [arXiv:1202.3415], Kuflik et al. [arXiv:1206.4201]...
- **Assumptions:** spin-parity 0^+, new other states are heavy enough, EWSB possesses a custodial symmetry, no FNCN at three level with the Higgs, kinematics not affected

$$L = c_V \frac{2m_W^2}{v} W_\mu^+ W_\mu^- + c_V \frac{2m_W^2}{v} Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b} b - c_\tau \frac{m_b}{v} h\, \bar{\tau}\tau$$
$$+ c_g \frac{\alpha_s}{12\,\pi\, v} h\, G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi\, v} h\, A_{\mu\nu} A_{\mu\nu} + c_\chi\, h \bar{\chi}\chi$$

- A simplified **model is recommended by the LHC Higgs Low Mass WG** [arXiv:1209.0040], to be used by ATLAS and CMS to measure Higgs couplings
- Higgs production cross-sections and branching ratios are scaled by various parameters
- **Coupling to bosons (κ_V) and fermions (κ_f):**

$$\text{Free parameters: } \kappa_V (= \kappa_W = \kappa_Z), \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$$
$$\kappa_i^2 = \Gamma_{ii} / \Gamma_{ii}^{SM}$$